

UCRL-CR--105118

DE91 002668

**A SYSTEM ARCHITECTURE
for
LONG DURATION FREE FLOATING FLIGHT
for
MILITARY APPLICATIONS**

**FINAL REPORT
August 31, 1990**

CIRRUS Aerospace Corporation
9817 Westwood Manor Court
Burke, Virginia 22015
By: Lawrence E. Epley

**Prepared for:
Lawrence Livermore National Laboratory
Under Purchase Order B089365**

MASTER

28

A SYSTEM ARCHITECTURE
for
LONG DURATION FREE FLOATING FLIGHT
for
MILITARY APPLICATIONS

TABLE OF CONTENTS

	Page:
1.0 INTRODUCTION	1
1.1 Background	2
2.0 MISSION ANALYSIS	3
2.1 Communications	4
2.2 Surveillance	5
2.3 Nonmilitary	5
3.0 SYSTEM ARCHITECTURE	7
3.1 The Balloon Subsystem	7
3.1.1 Analysis of a Superpressure Balloon	9
3.1.2 Altitude Stability	10
3.1.3 Dynamic Attitude Stability	11
3.1.4 Scaling Laws	12
3.2 Payload Considerations	13
3.3 Launchers and Lifting Gas	13
3.4 Network Connectivity	14
3.5 Navigation	15
3.6 Legal Infrastructure	16
4.0 MISSION PERFORMANCE REQUIREMENTS	17
4.1 Lifting Gas	17
4.2 Launch Considerations	17
4.3 Ascent	17
4.4 Duration	19
4.5 Observability/Vulnerability	19
5.0 MOBILITY	21
5.1 The Stratosphere	21
5.2 Global Circulation	24
5.2.1 An Annual Circulation Cycle Example	33
5.2.2 Sudden Warmings	41
5.2.3 Equatorial Circulations	42
5.3 Trajectories	43
5.4 Models	44

6.0	PROGRAM DEVELOPMENT	48
6.1	Project Objectives	49
6.2	Project Outline	50
6.3	Program Cost Estimate	50
APPENDDDIX A		52
BRIEF HISTORY OF LONG DURATION BALLOON DEVELOPMENTS		
APPENDIX B		53
SPP DESIGN ANALYSIS		
APPENDIX C		57
SOLAR TECHNOLOGY OVERVIEW		
REFERENCES		59

A SYSTEM ARCHITECTURE FOR LONG DURATION FREE FLOATING FLIGHT FOR MILITARY APPLICATIONS

1.0 INTRODUCTION

Accessibility is today's space frontier. Our need for wide-band global communications, earth imaging and sensing, atmospheric measurements and military reconnaissance is endless but growing dependence on space-based systems raises concerns about potential vulnerability. Military commanders want space assets more accessible and under direct local control. As a result, a robust and low cost access to space-like capability has become a national priority. Buoyant vehicles, free floating in the middle stratosphere could provide the kind of cost effective access to space-like capability needed for a verity of missions. These vehicles are inexpensive, invisible and easily launched. Developments in payload electronics, atmospheric wind modeling and materials combined with ever-improving communications and navigation infrastructure are making balloon-borne concepts more attractive. The fundamental question is whether a free floating balloon, used in a pseudo-satellite role, has value in a military system. Does current technology and the unique attributes of a balloon-based system offset their mobility limitation? We believe that for many missions the unique capabilities of a total balloon system will provide a capability unavailable with any other vehicle concept. The most significant attributes of a balloon-based system are:

- A. The cost of the flight vehicle can be as low as a few hundred dollars.
- B. Launch flexibility. Simple, robust techniques have been demonstrated and a hands-off launch is practical in many applications.
- C. Survivability/Observability. The vehicle and the launch operation is essentially invisible. The payload and its emissions are the only source of detectable signatures.
- D. Stability. Flight tests have shown that displacement from the vertical are very small, providing an excellent platform for imaging sensors.
- E. Earth Imaging. At 120,000 feet (20 nm) winds are generally less than 100 kts (50 kts is more typical). At that speed (100 Kts.), the angular rate with respect to the ground is about 0.04deg/sec compared to 0.7 deg/sec from a 400-mile satellite orbit.
- F. Mobility. Balloons float in the wind, making mobility a severe limitation. Improved wind modeling, launch flexibility and appropriate mission selection minimize the limitation.

CIRRUS, the Lawrence Livermore National Laboratories and Winzen International conducted a test of a Superpressure Balloon for the Defence Advanced Research Projects Agency (DARPA). The test was intended to validate a study by Winzen International Incorporated, and to proof performance models and manufacturing processes. Additional

flight tests are ongoing under NASA sponsorship. Following these tests NASA intends to use the vehicles for research in the Antarctic. The concept is being reviewed by other agencies interested in stratospheric research. We believe that LDFFF systems have applications in areas of communications, surveillance and other traditional satellite missions. Dialogue with the broader community of space users is needed to expand the applications. This report reviews the status of the recent flight tests and presents an overview of the concept of Long Duration Free Floating Flight for military applications.

1.1 Background: In 1783, two French brothers named Montgolfier flew a balloon carrying a duck, a rooster and a sheep. At about the same time a French chemist flew a hydrogen balloon to an altitude of 3,000 feet. By 1794, balloons were used in war as observation platforms. Through the years, balloons have been used for military communication, observations, and even bombing. The Japanese carried incendiary bombs to the west coast of the United States During WWII. In the 1950s, just before the U-2 aircraft became available, balloons were used by the United States to conduct surveillance over the Soviet Union. In the 1930's balloons were used for stratospheric exploration and the current manned balloon altitude record (113,000 feet or 34.7 km) was set in 1961. Interest in ballooning began to fall in the early days of the space race. Today balloons are used regularly for scientific observations and testing prototype space systems but the state of the technology has not advanced noticeable since the early 1960's.

In early 1987, a proposal for providing submarine communications in the Arctic was presented to DARPA. As a result, the Naval Technology Office within DARPA began a low-level effort to explore this and other balloon-based ideas. Concurrently, DARPA'S Strategic Technologies Office was investigating low-cost satellite concepts for tactical military applications. As a result of the low-cost satellite investigations, it became clear that creditable capabilities could be obtained in a light-weight and low-cost envelope and that military users needed a tactical access to a space-like capability that could be provided by simpler and less expensive systems. The superpressure balloon was proposed as an optional vehicle to provide space-like capability in carefully selected missions.

Two system concepts evolved from the early thinking: one was a simple, self-launched radio relay; the other was a superpressure balloon capable of free-floating at 120,000 feet for up to one year. The Navy quickly became interested in the self-launched radio relay and encouraged DARPA to demonstrate the capability. The project became known as Project ZEPHYR. A SBIR grant was issued to Winzen International in FY 1989 to study the current state of superpressure technology. The results of this study encouraged DARPA to conduct a flight demonstration. The first flight was conducted in March 1990 but a payload command problem prematurely terminated the flight. The next flight is expected in August 1990. This report will provide a description of the military applications, system architecture, military performance requirements and an assessment of the stratospheric dynamic transport of a total balloon-based military system.

2.0 MILITARY MISSIONS

The concept we present centers around a Long Duration Free Floating Flight (LDFFF) balloon-based system architecture. The key words are long duration and architecture. A system architecture is the conceptual arrangement of the functional elements making up the total end to end capability. Elements of a general balloon-based system include trajectory prediction, navigation, prime power supply, thermal control and others to be discussed later. In order to achieve an operational balloon-based capability, each element of the architecture must be developed and demonstrated in the context of a specific mission. Long duration flight refers to the ability of the flight vehicle to maintain altitude for indefinite periods. The current

goal is one year. We have chosen a superpressure balloon system, operating at 120,000 feet with a fifty-pound payload as a focal point for study and experimentation. The production cost goal of the baseline vehicle is \$20,000. Flights of one year in the stratosphere present challenges similar to those of space flight. The biggest challenge is to determine a priori trajectories of the vehicle through the use of stratospheric circulation modeling.

2.1 Analysis: In order to evaluate the application of balloons to various missions, we assume the following characteristics about the architecture:

1. **Vehicle reliability.** Off-the-shelf systems are capable of extended endurance (several months to over a year but well categorized). Ascent, float and recovery is predictable.
2. **Robust launch techniques.** Capability to launch from any point on the globe with short notice is required. Techniques for hands-off launch are available. Lifting gas storage and handling techniques are available. Encourage further development in launch technology.
3. **Legal concerns are not a factor.** Sufficient systems have been flown on a global basis and the international courts have allowed the balloons to be considered in international, freely navigable airspace.
4. **Vehicle stability over the long term must be well established.** Address reliability issues pertaining to payload and platform.
5. **Stratospheric wind models are operational and that sufficient stratospheric data are available to characterize long-term trajectories.**

These assumptions are reasonable and needed for further discussion of the various LDFFF missions. The mission categories that we consider are: (see ref 1,2,3 for additional details)

1. Communications. These missions are networks of communications nodes for wide-area communications, spot coverage for a particular surface area, search and rescue. Relevant technology demonstrations have been conducted.
2. Area Surveillance. This mission includes electronic signal intercept, agricultural and ocean survey, battle damage assessment, high resolution imagery, etc.
3. Earth Observation and Remote Sensing. This category includes study of global missions pertaining to meteorology, pollution monitoring, natural resource survey, auroral study. etc.
4. Astronomical Observation and Physics. This category includes solar physics, astrophysics, astronomy, space sciences, X-ray/gamma-ray astronomy, cosmic ray astrophysics, etc.
5. Space Hardware Test and Evaluation. This includes evaluation of sensors and support systems that must be recovered, or where low cost and accessibility are important prerequisites to space deployment.

2.1 Communications: The first concept presented to DARPA was a communications system. This system would provide large-area free-floating communication nodes in the Arctic. Eventually, the Navy determined that Arctic communications was not a requirement. The balloon-borne communications network concept continues to have merit in more general applications for several reasons.

1. Potentially a very low cost, global system. A balloon borne network with 300% redundancy and hemispheric coverage could be built for as little as \$75-100 M¹ (compared to \$400-600 M for a satellite, and several satellites are needed for hemispheric coverage).
2. Atmospheric attenuation of millimeter or optical wavelengths is minimal at the altitudes of SSV flight. These short wavelengths are capable of extremely wide-band transmissions and do not interfere with terrestrial or other balloon communications. They are also effectively unobservable from the surface because of atmospheric

¹. Based on a \$100,000 per node vehicle cost and a required coverage factor of 3X minimum. This network would be capable of full hemispheric telemetry.

absorption and antenna directionality. The result is that extremely wide-band widths and multiple simultaneous paths are available to the user.

3. The surface-to-transponder link path is comparatively short. Direct broadcast to a synchronous satellite involves a one-way link of over 25,000 miles. The maximum balloon surface-to-node distance is 350 miles. This allows for much simpler ground-based equipment.

4. Launch is easy and recovery is possible therefore space hardware reliability requirements can be relaxed.

The current state of technology supports off-the-shelf communications systems to adequately do the job. As described in Section 3.2, the principal elements of both the wide-band trunk and the controlling systems exist. In addition, direct broadcast TV, mobile communications and private data network demands are growing daily. As the Third World continues to develop, these demands will increase. Much of the Third World will build a communications infrastructure in the next decade and it is possible that free floating vehicles could be used instead of expensive microwave or other terrestrial-supported communications.

Military users stress reliability, flexibility, and robust operations in C⁴I systems requirements. A balloon-based communications system provides these features, either as a stand-alone system or as part of a supplemental system. A low-cost zero pressure balloon has been tested in a local area network role for special operations. This system is self-launched and provides short-term, area coverage within a 600-mile footprint for up to 24 hours. These systems are in various development stages and are the subject of separate work. Long duration systems are usable in theater level operations of more than 1500 miles.

2.2 Surveillance: Balloons were used for surveillance in the early 1950s over the Soviet Union and provided the only source of imagery before the U-2 was available. Launch flexibility, stability at altitude, low cost, and stealthiness make balloon platforms excellent candidates for certain types of area surveillance where the mobility limitation can be accommodated. Launch flexibility and cost are clearly advantages in a surveillance system.

Short flights have shown that balloons are very stable. However, long-duration flight vehicles will be subject to corollas acceleration and probably impulsing of the payload pointing system. Also, long-term platform stability has not been demonstrated. Very little aerodynamic damping is expected at normal operating altitudes and long-term payload stability could be an issue. High quality imagery requires a nadir to around 45° view. At the nominal float altitude, the balloon must be within 20 NM of the target. This requirement may be difficult to achieve and even with excellent atmospheric wind models.

2.3 Nonmilitary: Earth observation missions. There is considerable interest in the stratosphere as a result of concern about ozone depletion and atmospheric "greenhouse warming". Atmospheric chemistry or "aeronomy" addresses these and similar concerns.

Satellites have the capability to remotely sense large areas of the atmosphere, but these measurements have several limitations, primarily resolution and calibration. Long-duration free-floating balloons provide a natural platform for in situ measurements in geographically and temporally extended areas. A free-floating balloon can provide very fine resolution for a limited area and can be used for satellite calibration.

Satellites obtain wind data by measurement of critical wave-lengths of radiation emitted by atmospheric gases. From these measurements, temperature and geostrophic wind can be approximated. These measurements are difficult in remote areas because of the lack of data to initialize the algorithm and calibrate the system. The high percentage of cloud cover in the tropics add to the difficulty of measuring data and increase the value of in situ data. New satellites using limb sounders in addition to nadir sounders will be operational in the near future. The limb sounder relieves some of the limitations of the nadir sounder, but calibration data remain a major issue and a potential mission for LDFFF. The electrodynamics of the middle atmosphere is important because almost all of the energy absorbed and radiated by the earth interacts in the middle atmosphere (10-100km altitude). This area is difficult to explore in situ since it is too high for aircraft and too low for satellites. Rockets and zero-pressure balloons provide only short observations, consequently, very little is known about the temporal variations on time scales of days or months. Only long-duration balloons in conjunction with satellites and ground measurements allows for an accurate measurement of the electrical environment in the stratosphere.

The atmosphere is a barrier to the short wavelength, X-ray, gamma-ray and cosmic-ray emissions, of interest to astronomers. Observations of these emissions provide researchers with data needed for understanding solar flares, supernova, galactic and extragalactic x-ray sources, cosmic ray sources and properties of interstellar medium. This is a traditional area of balloon-borne research, but in all cases researchers need longer observation times. In general, the specific location for the flight is not a concern, therefore, the uncertainty of the balloon's location is not an issue. There has always been limited funding available for this type of research, and a cost effective LDFFF system is an attractive alternate to expensive satellites.

3.0 MILITARY BALLOON SYSTEM ARCHITECTURE

Figure 3.1 is a schematic illustration of a generalized military balloon-based system architecture to be used in Long Duration Free Floating Flight (LDFFF) and has the following subsystems:

- A. The balloon/flight vehicle, including self-monitoring, attitude sensors and flight controls;
- B. Payload support, including prime power, thermal control and a recovery system;
- C. Navigation and localization;
- D. Launch and ground handling systems, including lifting gas;
- E. Trajectory modeling, wind observations and climatological data;
- F. Command, control, telemetry and user interface;
- G. Balloon-to-balloon connectivity and networking capability;
- H. A legal infrastructure to allow unrestricted international flights.

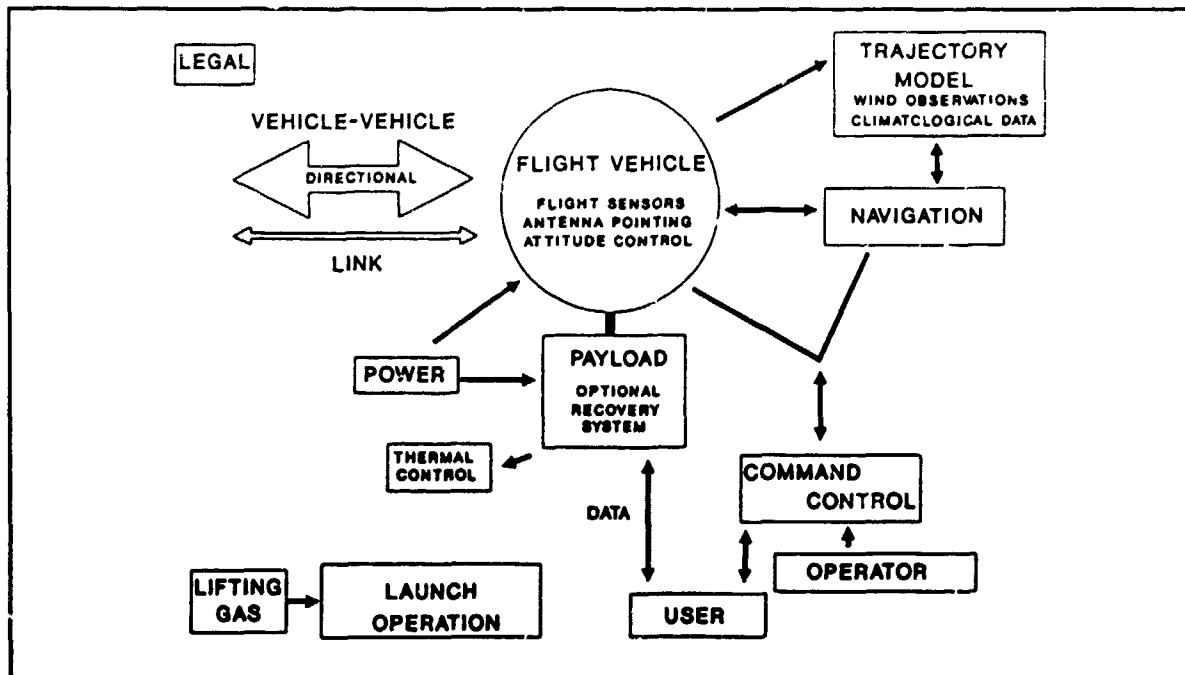


Figure 3.1 *Conceptual diagram of the total balloon-based architecture.*

In the following subsections, we provide an overview of each of these subsystems. The primary emphasis is on a military system operating at 120,000 feet for up to one year. Military balloon-based systems must achieve a high degree of operational reliability, otherwise, they will remain in limited, scientific or commercial use.

3.1 The Balloon Subsystem: In this section, we summarize key concepts and provide a

military user prospective on balloon technology as it applies to long duration flight. The Scientific Ballooning Handbook, reference 4, is an excellent description of the elements of balloon design and operation. A serious user should obtain a copy for design and analysis. The basic types of balloons are illustrated in Figure 3.2.

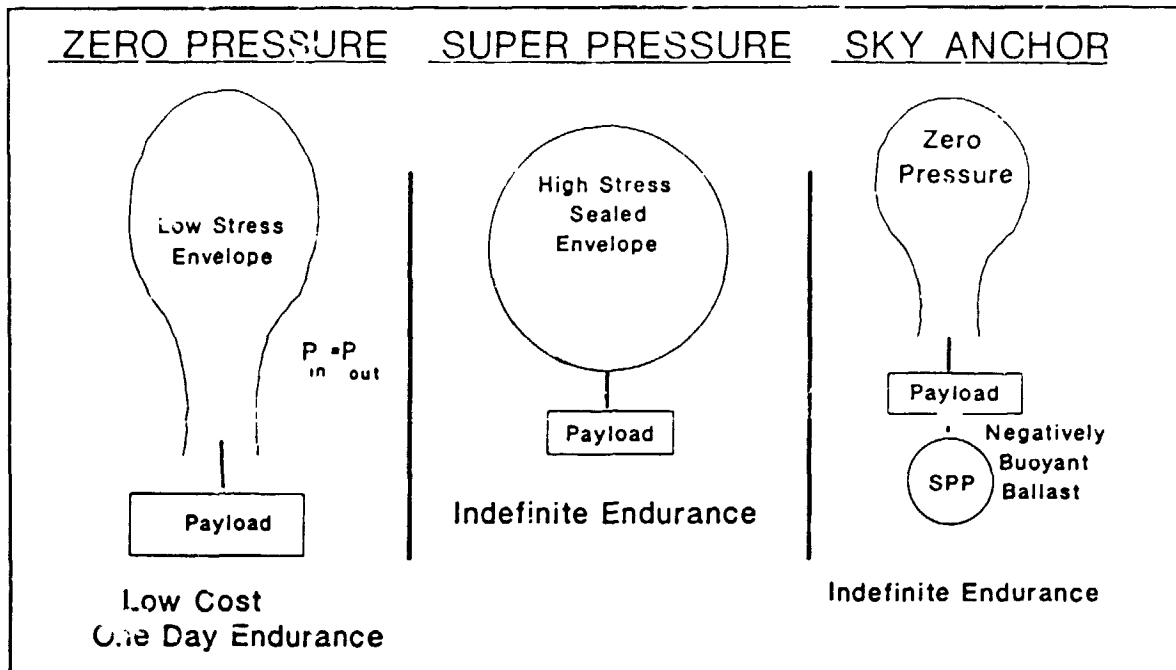


Figure 3.2 Illustration of the basic types of balloons.

The zero pressure balloon, or ZPP for Zero Pressure Platform, shown on the left, has been used for two hundred years and is the only kind in wide use even today. A light gas, such as hot air, helium or hydrogen is contained within a thin envelope. It is called "zero pressure" because gas is allowed to escape into the atmosphere to prevent overpressurization as the temperature increases. There is very little stress on the balloon envelope so it can be made thin and lightweight. This type of balloon routinely carries several thousand pounds of scientific payload to altitudes as high as 140,000 feet. At altitude, the sun heats the gas and causes it to expand and vent out of the balloon. At night, when the gas cools, the balloon volume decreases and it loses buoyancy. Dropping weight at night can extend the balloon life for a few days.

A variation of the ZPP, called the RACOON, is a very large envelope which is allowed to expand and contract, alternately ascending and descending with heating and cooling cycles. This technique is inherently unstable because the oscillations cannot be contained and the balloon eventually vents gas. A type of Racoon balloon is planned to be used in MARS exploration, reference 5. This balloon is stabilized using a chain hanging down and in partial contact with the surface. As the balloon rises, more of the chain weight must be supported by the balloon's buoyancy. With proper design, the system will remain stable indefinitely, ascending and descending, moving across the surface of the planet

gathering data along its path.

The Sky Anchor, pictured on the right in Figure 3.2, is a concept to stabilize the Racoon balloon and achieve extended flight. It uses an air-filled, pressurized balloon as an air ballast to stabilize the platform. As the upper ZPP ascends due to warming, the lower balloon becomes heavier than the surrounding air. This "virtual weight" stabilizes the platform and prevents it from continuing to ascend to an altitude where gas would be vented.

The super pressure balloon or SPP is illustrated in the center of Figure 3.2. It is a sealed, pressurized envelope. The total system density is fixed and, ideally, this structure floats indefinitely at a constant density level. The envelope must, however, accommodate the high-tension loading that results from the internal pressure. The material must be thin and lightweight, the seams must be flawless, and the film free of pinholes and impermeable to gas diffusion.

A brief history of balloon developments in long duration flight is contained in Appendix A. Both SPPs and Sky Anchors have been tested in LDFFF applications. Sky Anchors, however, have very little success history. Their poor record is generally attributed to the complexity of the launch operation and the vulnerability of the SPP mylar material. SPPs have been used in several projects, particularly at the National Center for Atmospheric Research, NCAR. These balloons were comparatively small and the ability to scale the design to large SPPs has always been challenged. Large SPPs are vulnerable to launch, handling, and quality problems. SPP Technology is a basic technique needed for Long Duration Free Floating Flight and understanding of the design factors are generally thought to be the primary requirement limiting for LDFFF.

3.1.1 Analysis of a Superpressure Balloon: This section is intended to provide a fundamental analysis of a superpressure balloon. A detailed engineering analysis is contained in section seven. Equation 3.1 provides useful insight into the important elements of the SPP design. The derivation of equation 3.1 is given in Appendix B. The net lift of a superpressure balloon is the difference between the buoyancy and the structural weight. The structural weight depends primarily on the skin film weight which is a function of the pressure differential and balloon size. Expressing that relationship and assuming that the envelope thickness is a continuous and free design parameter which is a function of the internal pressure allows us to develop a simple equation to relate the fundamental design considerations.

$$\text{Gross Lift} = P_{\text{air}}(h) \left(\frac{MW_{\text{air}} - MW_{\text{gas}}}{R_0 T_{\text{air}}} - 1.5 \frac{\rho_m}{\sigma_m} \left(\frac{T_{\text{max}}}{T_{\text{min}}} - 1 \right) \frac{P_l}{P_{\text{air}}} \right) \text{Vol}(r) \quad (3.1)$$

Where:

$$P_{\text{air}}(h) = P_0 e^{\left(\frac{-h}{\text{Scale Height}} \right)}$$

The three terms in equation 3.1 represent the ambient air pressure, $P_{\text{air}}(h)$, the center term containing all of the specific balloon design parameters, and the volume term, $\text{Vol}(r)$. Gross Lift includes seams, fixtures and load lines which are functions of the radius r , and surface area (r^2). These smaller effects have been included in Gross Lift in order to illustrate the most basic design points. It can be seen that the lifting capacity is related to the volume and to the float altitude. Pressure obeys the hydrostatic relationship and is an exponential function in height. The balloon design term shows the effect of the lifting gas's molecular weight and outside air temperature. The super temperature ratio, $T_{\text{max}}/T_{\text{min}}$, is a design choice that depends on the assumed operational conditions, solar radiation and the envelope's thermal properties. A pressure ratio term, P_l/P_{air} , is shown in the equation to illustrate the fact that the balloon is usually designed as to maintain a slight overpressure at the minimum design temperature condition. The importance of low weight to strength, (ρ/σ) , material is also shown. See section seven for additional design considerations.

Determination of the exact amount of lifting gas is important. If too much gas is used in the balloon, it becomes overstressed at the highest expected internal temperature and fails. Too little gas results in underinflation at night. The underinflated night condition can cause an unstable float and loss of the balloon in extreme cases. Choosing a supertemperature ratio that accounts for varying conditions is difficult, especially when extended global flight is planned. Additionally, the actual volume of the balloon at float can be difficult to determine within 1% without carefully controlled fabrication procedures.

3.1.2 Altitude Stability: There are four factors which will cause altitude deviations of a superpressure balloon. They are:

- a. Elastic deformation of the balloon film;
- b. In-elastic deformation of the balloon film (creep);
- c. Non-standard temperature or pressure at float altitude;
- d. Loss of lifting gas.

Material deformation can result in altitude excursions which can increase and decrease the pressure differential and internal film stress. The effect of non-standard conditions at float must be considered in the design process. This is particularly critical in long duration flight where different conditions will be encountered. The density of the

balloon is theoretically known by design and the float height, pressure and temperature in standard conditions. The US Standard Atmosphere provides an appropriate basis for determining flight conditions. From the ideal gas law we can state:

$$\rho_{air}(h) = \frac{P(h)}{RT_{air}(h)} \quad (5.2) \text{ and:}$$

$$\frac{T_2}{T_1} P_1 = P_2 \quad \text{From the Perfect Gas Law}$$

For small altitude changes we can assume that the balloon's altitude can be determined its density for specified conditions. The ambient pressure where this density occurs, however, will change as a result of nonstandard temperatures. A decrease in ambient temperature will result in a higher density at a given pressure. The balloon will rise to maintain a constant ambient density and the ambient air pressure will be lower. Because the balloon has a fixed amount of gas, the pressure difference across the envelope will increase, resulting in higher stress due to superpressure. The internal balloon temperature will not be noticeably affected.

To illustrate, consider a situation where a balloon is launched and is initially at equilibrium at 120,000 feet where the temperature is -30°C and pressure is 5 mb. As it floats around the globe, the temperature at the 5 mb pressure level becomes -45°C. As the balloon floats into the colder temperatures, it rises until, at -45°C, it has risen to an ambient pressure of 4.7 mb - 0.3 mb lower or about 2000 feet higher. The temperature will vary slightly when the balloon rises but this effect is negligible (+2.5°C per km is typical at this altitude). If the internal temperature remain constant (a good assumption because absorption, radiation and incident energy have not changed), then the pressure differential and maximum stress increase by 6%. This loss of stress margin can be critical and the design must allow for atmospheric conditions in the expected flight conditions.

Loss of lifting gas initially causes the balloon to rise because the system is losing mass. This change is difficult to observe but, eventually, the balloon will not maintain superpressure in the coldest part of the flight profile. In extreme cases, the loss of altitude will become unstable and the balloon will not recover. This effect is not as critical at 120,000 feet because of the positive ambient temperature gradient; but, at about 70,000 feet, where the atmosphere becomes isothermal, loss of pressure will cause an unstable loss of altitude.

3.1.3 Dynamic Attitude Stability: The Scientific Balloon Handbook, reference 4, describes zero pressure balloon dynamic stability. A superpressure balloon will behave in much the same way and move up and down as a result of gas temperature changes that cause it to expand and contract. A superpressure balloon that is displaced from its buoyant altitude will be subject to a restoring force that is proportional to its volume, and it will oscillate about

its base altitude until the motion is damped by aerodynamic forces. The natural period of oscillation varies from 160 to 180 seconds depending on air temperature and lapse rate. It will also rotate slowly in order to conserve angular momentum as it moves up and down. Experience with zero pressure balloons indicates that these motions are strictly rotations and translations of the balloon's vertical axis. There is, however, very little aerodynamic damping of this motion because of the low air density at the nominal flight altitude. It is reasonable to expect that over a long period there will be some coupling of these motions into the other balloon axis, but little flight data exist to confirm this supposition. An active pointing system that requires the balloon's inertia to provide a reactive force is needed in many applications. The energy that is added to the balloon by the pointing system will add to the complexity of the motion. These motions could grow large and may need to be dissipated artificially before the system oscillations grow too large for the tracking and pointing system. This is a speculative issue because long term flight data do not exist, and the amount of natural aerodynamic damping is unknown.

3.1.4 Scaling Laws: The ability to scale up a superpressure balloon has always been a concern. Cost, reliability and physical size are potential issues when a superpressure balloon is scaled to larger payloads or higher altitudes. Equation 3.1 implies that weight and altitude trade equally with increase in balloon size. Larger sizes, however, will have an increased probability of a material or fabrication flaw that cause balloon failure at altitude. A large balloon is also more difficult to launch. A generalization of balloon costs could be stated as:

$$COST = MATERIAL + SEAMS + LOAD LINES + FIXTURES + QA + PACKAGING + PRODUCT LIABILITY$$

Typical balloon film costs three to five dollars per pound. There is also about a 60% waste factor in fabrication. From Equation 5.1, we can see that the weight of film is proportional to the gross lift. Therefore, the film cost for a balloon system is also proportional to the payload weight. Prototype or special material could easily cost two to three times more but may lower total unit cost because of much higher strength to weight. Materials with twice the strength of current films have been tested in prototype form. These materials dramatically lower the size and weight of the balloon. Many of these material developments have not matured because the total consumption of balloon film relative to other film materials produced by the plastics industry is extremely small.

The seaming process is very labor intensive and can be expressed as a cost per foot of seam. The total seam length is $4\pi^2 r^2$. Other labor categories, such as material surface inspection, are related to the surface area of the balloon film.

The general conclusion is that scale-up economics appears to be favorable because the material costs are proportional to the volume which is, in turn, proportional to the payload weight. The labor factor appears to proportionately decrease with increasing size. Quality and launch factors are thought to obey similar relationships.

3.2 Payload Considerations: Two major payload considerations are prime power and temperature control. The most likely power system uses solar-charged batteries. Fuel cells use hydrogen and oxygen separated by a membrane to generate an electric potential. Fuel cells, operating with low pressure air instead of oxygen, have been proposed for balloon applications, but the technique has not been demonstrated. Emerging solar technology is critical because of the high value to the total system of a lightweight subsystem. Appendix C is a brief summary of commonly available solar technology. Battery operation at low temperatures is a concern that must be considered in the design.

Because of the low air density, outside air temperature at the high altitude plays a small role in the temperature of the payload. Solar absorption, power dissipation of electronic components, radiation and surface conduction establish an equilibrium temperature that is generally different than the air. The equilibrium point is usually too hot or cold, making thermal control mechanisms similar to those used for spacecraft necessary for long-endurance flights. A good example of a simple thermal control mechanism is described in reference 6.

3.3 Launchers & Lifting Gas: Tactical use of balloon systems has been limited by packaging, handling and storage of lifting gas. Today, lightweight payloads greatly simplify the problems encountered in the past because capable balloon systems are much smaller. There are three primary candidates for lifting gas: helium, He - molecular weight, 4; hydrogen, H₂ - molecular weight, 2; ammonia, NH₃ - molecular weight, 17; and decomposed ammonia, N₂+3H₂ - molecular weight 8.5. Unfortunately, there are limited options available for gas storage. As we have seen, doubling of payload weight requires doubling the amount of lifting gas needed. Helium has always been the first choice in lifting gas for safety reasons, but helium can only be stored in a pressurized or cryogenic form. Additionally, sources of helium are limited and it is sometimes difficult and expensive to obtain.

All lifting gases can be stored in pressurized containers. A Navy program, for example, used a specially developed, filament-wound bottle capable of 15,000 psi internal pressure. Standard pressure tanks carry a maximum of 3,000 psi. These containers have not been acceptable to the users because of cost and potential dangers. For a 50 lb payload, a 3,000 psi bottle would need to have an internal volume of 4 cu ft (12 inch dia X 5.1 feet long internal dimensions). At 3,000 psi, each pound of lift at sea level requires 0.08 cu ft of internal storage volume. While pressurized gas is not portable, it is inexpensive and easily available for use where portability is not a factor. Cryogenic tanks are readily available and can be used for efficient gas storage in larger facilities.

Hydrogen can be obtained from numerous chemical reactions but it is flammable. There have been several hydrogen-generating concepts tested in order to reduce the weight and size of the lifting gas subsystem. The DARPA Zephyr communications system used a calcium hydride and water reaction to generate hydrogen lifting gas. This technique was satisfactory for the concept demonstration but was too slow and too large for a 70 pound payload system. A small, solid hydrogen-generating system was developed for use in a signaling device for downed aviators. The generator was 12 cubic inches in volume and

produced 130 liters of hydrogen in 12 seconds. This type of device could be modified for use as a gas source for SPP's operating in remote areas. Ammonia has interesting properties as a lifting gas. It is liquid at reasonable temperatures and pressures and has about half the lifting value of helium in its gaseous state. It will absorb heat changing from a liquid to a gas and could be decomposed with additional heat into hydrogen and nitrogen with a total molecular weight of 8.5. The decomposed gas has about 70% of the hydrogen's lifting efficiency. Because Hydrogen-generating reactions create a lot of excess heat, the two processes could be complimentary. Full-scale prototype systems have not been built, but several have been demonstrated in a laboratory. A reverse fuel cell design was proposed to DARPA in the early phases of the program that would use electric power to generate hydrogen from water. It is relatively simple but required considerable electric power. Hydrogen handling is an important factor but is usually misunderstood by potential users. Typically, the dangers are overstated and care must be used in forming hydrogen concepts to insure that users are adequately informed about the safety issues.

3.4 Network Connectivity: A network is a group of balloons that form a path or "umbrella" that passes data over a large area. The user interface is the access to the network. In the general case, the network serves multiple users and must carry more data than any single user interface. It must therefore have a wider bandwidth capability. At some point, the bandwidth requires that the system use a directional antenna to transmit frequencies and bands capable of the higher data rates. The use of the directional antenna adds considerable complexity to the system design.

Conceptually, a general system will require both directional and nondirectional elements. Because the positions of the individual balloon nodes change relative to the ground the user will probably be limited to nondirectional capability. The general architecture would include both. A nondirectional system will be needed to transmit housekeeping data and position information even where a directional antenna is used. Antenna pointing presents several mechanical issues that were discussed in a preceding section.

At the altitude of SSV operations, the atmosphere presents very little attenuation at optical or millimeter wave-lengths. The lower atmosphere, however, highly attenuates these signals, selectively. This presents two opportunities: one, wideband communications can be transmitted over long distances or uplinked to a passing satellite without being detectable from the ground; secondly, spectrum allocation is not an issue because these frequencies are not used in ground-based systems. This feature is useful in both communications and surveillance. All the key system elements have been developed for other applications, such as space communications and are off the shelf.

To support large area connectivity, protocols for autonomous system control must be developed. Packet switch radio systems have been in existence for some time, and low cost "ham radio" versions are easily available. The "Low Cost Packet Radio" developed by DARPA in 1987 is an example of a sophisticated autonomous system that provides a balloon system with a great deal of operational flexibility. A packet is a bundle of data bits that are

handled like mail. The bundle is given an address, a sender ID and transmitted on a carrier frequency. The individual relay nodes see the movement of these bundles along with their intended routing. By inference, each node builds a look-up table and eventually develops the capability to route any packet it receives to any destination in the network. The network of individual packet nodes becomes self configuring and can autonomously respond to a loss of a node or jamming in a particular area.

3.5 Navigation: The development of the Global Positioning System, GPS, dramatically impacts the capabilities of long duration free floating flight systems. Small and relatively inexpensive platform receivers are capable of resolving highly accurate three dimensional fixes anywhere in the world. There are at least 42 companies worldwide making GPS receivers for applications that range from military missile systems to civil aircraft and ground surveyors. Performance also varies widely from sub-meter accuracy to 100 meters in the low cost civil use versions. A full function military system could cost \$100,000 but low cost civil sets cost as little as \$3,000 and weigh about one-half pound.

GPS relies on a constellation of 24 satellites with three spares in a 11,000 mile orbit. An extra satellite is planned to be in orbit as a standby. The system will be fully operational in 1992 but is usable today with occasional dropouts in coverage. Navigation is accomplished by observing the satellite signals, measuring the transit time/distance of the signal from the satellite to the receiver and solving for the three receiver position coordinates and GPS system time. This process requires that four satellites are in view at the same time. When fully deployed, four satellites are guaranteed to be in view always. The satellite signals are modulated with two codes. The "P" code is a pseudo-random sequence that allows military users with the proper description capability to obtain fixes of ten meter or better accuracy. The less accurate "C/A" code is used for capture and is available to civil users. The stated accuracy of C/A without P is 100 meters but 25 meter fixes can be obtained under some conditions. Low cost receivers sequence between satellites using one, two or three channels until enough information is collected to determine a fix. In slow moving platforms such as a balloon, these techniques are quite effective.

The Defense Department has the capability of limiting the accuracy of GPS information to non-defence users. This is done by introducing inaccuracies into the satellite ephemeris data. This procedure is referred to as selective availability. It is doubtful however that the degradation will exceed 100 meters and should not be a factor in balloon systems.

GPS is not the only satellite based navigation system. The Soviets have a system called Glonass and the Navy has a system called Transit. GPS however has received a considerable technology push from the Defense Department. For example, DARPA developed a pocket sized GPS using a highly integrated chip set. Based on wide usage, many companies have invested in low cost civil receivers for applications such as pleasure-boat navigation. Interest in satellite navigation for global civil aircraft navigation and control led the FAA to fund Lincoln Laboratory to develop a dual GPS/Glonass receiver. As of this time one GPS receiver has flown on a balloon flight for NASA. The receiver was a two

channel set and proved the value of balloon borne GPS system. Satellite navigation by GPS is the only practical method of navigation for LDFFF.

3.6 Legal Infrastructure: There is no existing legal infrastructure to support international long duration ballooning. A scientific balloon under close observation and launched in carefully selected conditions presents no unusual legal complications. On the other hand, a free floating SPP with a mission life of a year or more is very different. International air traffic regulations generally extend to 60,000 feet with military monitoring extending to 100,000 feet. Orbital space is a tacit international zone much like open oceans. But free access to the middle stratosphere is unlikely to be treated the same way. Two significant issues must be addressed by international law: one is the territorial sovereignty of the country being overflown, the other is coexistent air traffic and the safety of persons on the ground.

Sovereignty is a complex issue which ultimately is settled in international court. Similar legal issues are academic unless a country has the capability to detect and enforce its territorial claim. In the case of long duration flight, the combination of altitude and observability make pressing a claim difficult. As an example, Columbia claims that a US communications satellite in a synchronous orbit directly above is an invasion of its territorial airspace. This claim has been mostly ignored because it is unenforceable. The sovereignty issue was raised to the chairman of the AIAA technical committee for Aerospace Legal Issues and to the Director of Space Commerce, US Department of Commerce, and both agreed that LDFFF at high altitudes is an undefined area of international law.

Air traffic control procedures that govern the ballooning operations exist in all countries. In general, these regulations do not govern flight in the middle stratosphere. Ascent and descent restrictions do exist but should be standardized. Under earlier superpressure flights by NCAR operated near the tropopause where aircraft operate. Aircraft frangible payloads were used to prevent catastrophic damage to aircraft. These payloads had a low density and would break up on impact with an aircraft. Aircraft frangibility, as well as other issues, will require an international body of regulation. Acceptable standards, particularly for commercial applications, are needed to limit operator liability.

4.0 MISSION PERFORMANCE REQUIREMENTS

There are three major areas where the mission requirements determine fundamental balloon system parameters: positioning accuracy, size and telemetry, and altitude and duration.

4.1 Lifting Gas: The availability of lifting gas has been a major limiting factor in the development of military balloon-based systems. For example, several attempts at the Air Force Geophysics Laboratory, AFGL, have failed to produce a deployable Air Force system due mainly to the complexity of the gas and inflation. Of the potential lifting gases available, only hydrogen and helium have been considered in any detail. Helium tankage is a problem as discussed previously, and hydrogen can be produced as needed by the system through several chemical reactions but is flammable. The packaging, handling and storage issue is the most important problem facing a potential military system. Ideally, the source is portable and low cost and could be stored aboard ships without presenting a safety issue. More work against mission requirements is needed in this area.

4.2 Launch Considerations: Balloons are most vulnerable during launch. Large scientific balloons require elaborate ground handling facilities and optimum flying conditions. The LLNL developed a shipboard launch system for use in its KESTREL program. The system was a hands-off launcher that carried a 1500-pound payload to altitude. Military systems require all-weather, and hands-off operations similar to the KESTREL system. There are several initiatives in ZPP to develop launch robustness and similar techniques can be applied to SPPs.

4.3 Ascent: Small balloons will generally ascend at a nearly constant rate of about 700 fpm; larger ones typically ascend at around 1000 FPM. These ascent rates are generally acceptable to users. There is little difference in the dynamics and performance analysis between an SPP and a ZPP during the ascent. The subject is described well in the Scientific Balloon Handbook, but a brief discussion is appropriate here. Climb speed is the result of the balance between buoyancy, lift, and the drag resisting the upward movement. These relations are:

$$\text{Lift} - \text{Buoyancy} = g \text{Vol}(r)(\rho_{\text{air}} - \rho_{\text{gas}})$$

and

$$\text{Drag} = \frac{1}{2} C_D \rho_{\text{air}} V_{\text{climb}}^2 \text{Area}$$

The factors affecting the climb speed are:

1. Free lift. Free lift is the amount of excess volume needed for neutral buoyancy. It results from excess lifting gas and is usually expressed as a percentage of the total system weight. It affects the initial acceleration and the rate of climb. An SPP will usually have a higher percentage of free lift than a ZPP because of the excess gas used to maintain superpressure under the coldest expected conditions.

2. Balloon Drag. Drag, as determined by the above equation, depends primarily on the drag coefficient which in turn depends on the Reynolds number, Re^2 . For Re greater than about 4.5×10^5 , the flow is turbulent and C_D is about 0.3. For smaller Re , C_D is around 0.45. Thus, smaller balloons have slower ascent rates.

3. Gas Temperature. As the balloon rises, the gas expands adiabatically to equal ambient pressure. The lapse rate for helium is about the same as air, but hydrogen cools faster than air as the pressure decreases. This effect will lower the ascent rate of a hydrogen balloon. Additionally, a hydrogen balloon will damp motions at altitude.

4. Ambient Temperature. Dry air will cool adiabatically as it expands at altitude. At lower altitudes, air always contains water which modifies and warms this "dry adiabat" cooling rate. Additionally, the state change of water from gas to liquid and again to solid releases latent heat, causing the temperature to rise. The net result is that the outside air and internal gas temperatures are usually different and the difference modifies the ideal ascent rate.

5. Water and Ice Accumulation. While scientific balloons are not usually flown in these conditions, military systems could encounter these conditions. Water accumulating on a balloon will add weight and could cause the balloon to stop climbing. As the balloon climbs into the sun, the water should evaporate, particularly in the stratosphere above 40,000 where there is almost no water and the relative humidity is nearly zero. In a test of the DARPA Zephyr, the balloon ascended through an area of probable rain and ice without significant loss in rate of climb but this was a single test and the results are not definitive.

6. Winds. Vertical or shear winds are typical in areas of unstable air and high humidity. The violent downdrafts can be impossible to climb in. In extreme cases, this

² The Drag coefficient, C_D , and the Reynolds number, Re , are non dimensional quantities used to determine aerodynamic properties of a system. The drag coefficient is evaluated for a system by measuring drag and computing C_D based on a characteristic area. In the case of balloons C_D is based on the frontal area of the balloon spherical bubble. Re is $\rho L \text{ Velocity} / \mu$ where the characteristic length, L , is the balloon diameter and μ is the viscosity of the fluid. This quantity is used to determine if a flow is laminar or turbulent as it passes around a body.

unstable air generates thunderstorms.

Several options are available to improve climb performance. The amount of lifting gas can be increased, but as stated earlier, SPPs already have excess lift at the surface. The expansion might be constrained early in the flight so that the balloon expands in a "sausage" shape so as not to increase its frontal area. Turbulent flow can be induced early to decrease C_D to using an effect much like the dimples on a golf ball. Night launches could present problems because of the cold gas and inability to evaporate water. A rapid ascent to float for a SPP can cause an overshoot which might burst the balloon.

4.4 Duration: A mission duration is limited by the payload life, the usefulness of the trajectory, and the life of the balloon itself. Ideally, a superpressure vehicle will last indefinitely. A real balloon, however, will lose gas by diffusion, deteriorate from UV radiation, or eventually fail because of a manufacturing flaw. The manufacturing process is the most probable cause of failure. The payload may also have a limited life because of component reliability and prime power. The mission may require a certain trajectory which degenerates over time.

The goal of a one-year endurance for the SSV came from the desire to lower the cost of a large area communication network where the location of the system was not critical. Ideally, a long-life system would lower the cost. As alternate missions were proposed, it became apparent that most did not require the full-year life but that the payloads often were expensive and some required recovery. The ability to allow a vehicle to overfly a target and float to a convenient location, perhaps circumnavigating several times before recovery, became attractive. A Persian Gulf overflight, for example, might be launched in the Mediterranean, overfly the area of interest, pass the data to a satellite and recover the payload in Florida a month later.

4.5 Observability/Vulnerability: Low observables; an operating environment at 120,000 feet; redundancy because the low cost allows for a number of vehicles to fly a mission if needed combine to give a balloon system unique survivability characteristics. Visibility in the RF spectrum has been shown to be extremely low. Adding to the difficulty of radar detection is the low doppler because of the low speed. There is more uncertainty about IR and optical signatures. The balloon's temperature will be higher than the surrounding area, and the system could be viewed against space as a background providing a high IR contrast. At the right wavelengths, the system can be expected to have good contrast but requires a good sensor resolution to be visible. Visual detection is probably the most detectable signature. The surface is "shiny" because of the nature of the film. It is exposed to sunlight for about an hour after sunset on the ground so that it looks like a bright star at dusk. There has not been a systematic measurement of the true visibility of the system.

Neutralizing a balloon is not easy, and a neutralization system would be very expensive. A weapon must be able to operate in a near-space environment and find a low visibility target. A ground-based laser or kinetic energy weapon might be used, but it

requires precise pointing and its energy will be highly attenuated in the lower atmosphere. Finally, the low cost and relative ease of deployment allow balloon-based systems to be deployed in numbers that guarantee overall mission success.

5.0 MOBILITY:

Mobility is the ability to effectively use the environment for transport of Long Duration Free Floating Flight vehicles. Each particular mission has unique requirements to place a balloon at a specific position in time and space. The ability to construct useful missions which rely on uncontrollable wind patterns is among the most important issues facing the exploitation of LDFFF. The stability, predictability, and observability of the air flow patterns must be determined in order to assess the application to candidate missions. The fundamental questions that potential users ask are:

1. What are the long-term trends? Do balloons over long periods of time get hung up in localized patterns?
2. What is the stability and predictability of the long-term patterns? Will balloons remain in a usable trajectory over a long period of time?
3. Can a specific point on the earth's surface be overflown with enough precision that the system can be used for high quality imagery?
4. Given better data sources and improvements in wind modeling, can we dramatically improve our ability to use the transport mechanisms?
5. Will a small amount of thrust or altitude control provide long-term trajectory control?

While the stratospheric dynamics have been studied for many years, these specific questions that apply to balloons floating at a constant density have not been of interest. Additionally, the question of a long term track of a particle has not been studied. Most of our understanding of the stratosphere results from the need to predict tropospheric weather. Recent interest in ozone depletion has led to additional interest in stratospheric dynamics, but our understanding of the process is still limited. Data and an operational requirement for trajectory prediction are the principal factors limiting our understanding. The following sections are intended to provide some insight into the problems and assess the current understanding of stratospheric dynamics relative to the above issues. Ultimately flight data will be needed in order to adequately address the ability of using stratospheric dynamics as a transport mechanism.

5.1 The Stratosphere: In order to understand the trajectories, we must first understand the dynamics of the stratosphere and the terms used in meteorology. Pressure and temperature are the two most fundamental measurements needed to describe the condition of the stratosphere. Ambient air pressure in meteorology is given in units of millibar (mb)³. Typically, the pressure-height relationship is depicted on charts of constant pressure, with

³ A bar is a unit of pressure equal to 14.5 lb/sq.in or about one atmosphere so that a millibar is about 0.1% of sea level pressure.

height as the free variable so that the height where the stated pressure is found is plotted. Points of equal height are connected to form height contours on the constant pressure chart. These contours provide a picture of the pressure patterns across the globe. 120,000 feet nearly corresponds to the 5mb pressure level which is one of the points where meteorological analysis is focused. Most of our work in this section will use the 5 mb level for discussions and example. Heights are given in terms of their geopotential value (meters or decimeters) which, for our purposes, is the same as actual height above sea level. Winds are either in meters per second or knots. Table 5.1 is a list of the commonly referenced points in the stratosphere and is given to provide the reader with an overall perspective. The terms "zonal and meridional wind" are used throughout the literature to mean winds parallel (zonal) and perpendicular (meridional or parallel to meridians) to the equator.

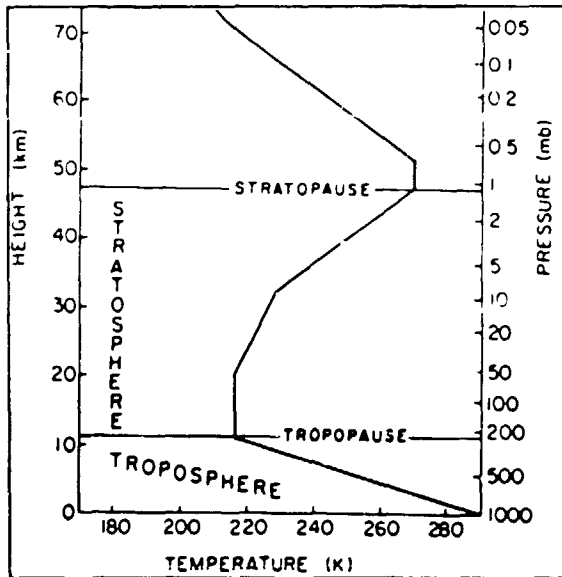


Figure 5.1 Temperature profile of the Standard Atmosphere. Notice the sharp change in slope at the Tropopause, the lower boundary of the Stratosphere. (U.S. Standard Atmosphere, 1976)

STRATOSPHERIC REFERENCE POINTS

<u>HEIGHT(ft)/(km)</u>	<u>PRESSURE(lb/ft²)</u>	<u>PRESSURE(mb)</u>	<u>T/T₀</u>
Sea Level	2116	1015	1.000
36,089 (11.0)	473	226	0.752
50,000 (15.2)	242	116	0.752
67,500 (20.6)	104	50*	0.752
70,000 (21.3)	93	44	0.752
82,621 (25.2)	52	25*	0.752
100,000 (30.5)	22.6	10.8	0.809
101,860 (31.1)	20.9	10*	0.810
117,000 (35.7)	10.4	5*	0.850
120,000 (36.6)	11.0	5.25	0.870
140,000 (42.7)	4.6	2.2	0.936
141,000 (43.0)	4.2	2.0*	0.940
150,000 (45.7)	2.9	1.4	0.967

Table 5.1 Pressure, heights and temperatures for various altitudes of interest in the stratosphere. The "*" indicates a height where atmospheric data are available. 36,089 feet is the nominal height of the tropopause or lower boundary of the stratosphere in the mid-latitudes.

The stratosphere is fundamentally very different than the troposphere where we live. Figure 5.1 is a representation of atmospheric temperature. Notice the sharp change in slope at the tropopause where atmosphere becomes isothermal with increasing altitude. This is the tropopause or lower boundary of the stratosphere. In the troposphere, water plays a major role in the temperature balance. Above the tropopause and into the stratosphere,

water is almost nonexistent and absorption and radiation of solar energy by atmospheric gases, such as ozone, dominate the thermal balance. Terrestrial radiation, molecular diffusion and ionization do not play a major role as they do in other areas of the atmosphere. Figures 5.2 and 5.3 show the global scale temperature and

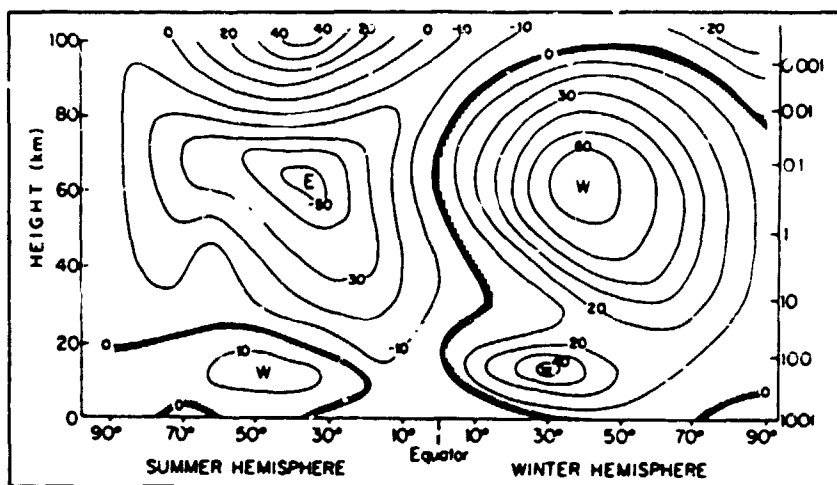


Figure 5.2 Average Global winds. (R.J. Reed)

mean zonal winds. The mean zonal wind is the east-west wind component averaged around the globe. The "jet stream" at the stratosphere-troposphere is clearly seen, as well as a minimum wind zone in the lower stratosphere at around 20 km. Notice in Figure 5.3 that the warmest temperatures in the stratosphere are in the mid-latitudes as opposed to the tropics as one would expect.

Conservation of total energy, momentum, and mass are required throughout the stratosphere. On its own, the stratosphere would remain simple and stable, but the sun's constantly changing position relative to the earth, combined

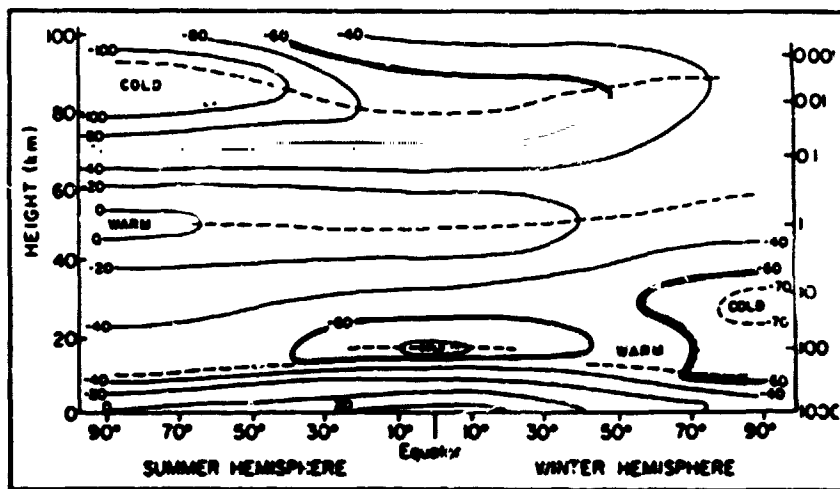


Figure 5.3 Average Global Temperatures. (R.J. Reed)

with variable absorption and radiation over land, sea and clouds, as well as the mechanical convection from mountains, called orography, propagate energy into the stratosphere. Two fundamental processes occur simultaneously and combine to give the stratosphere complex dynamics. One is the thermal balance of incident solar radiation, the absorption of solar

energy by ozone, and the radiation of the resulting thermal energy by carbon dioxide, CO₂, into space. Infrared emission of carbon dioxide is approximately balanced with ozone UV absorption, and the relative concentrations of these atmospheric gases at a specific height determines the equilibrium temperature. The second fundamental process is the dynamic motion of the rotating fluid, air.

Disturbances in the stratosphere occur on global scales. The short-scale weather phenomena in the troposphere are heavily damped or filtered from the stratosphere for several reasons. Since CO₂ radiation is a function of temperature, large temperature differences in a local area cannot be maintained because of differential radiation. Therefore, the stratosphere cannot support large horizontal temperature gradients, and it acts as a filter, blocking and averaging localized patterns which are common in the troposphere. In the northern hemisphere winter dynamic conditions allow long stationary patterns or waves to exist in the presence of westerly winds above a critical velocity. This velocity depends on the latitude and the wavelength. This makes the northern hemisphere winter a special case of stratospheric motion.

Gravity waves resulting from orographics will promulgate upward into the stratosphere. This phenomenon perturbs the wind patterns on scales of a few miles. Because it is a pressure-density relationship and not related to temperature, and they are a comparatively small scale, they are difficult to resolve with current space-based sensor systems.

5.2 Global Circulation: For the purposes of long-duration ballooning, global circulation can be divided into four types of motion.

1. Geostrophic winds resulting from synoptic scale pressure distributions in the higher latitudes of each hemisphere;
2. Stable, steady winds in the tropics within 20° of the equator;
3. The boundary and transition between these regions;

Local effects resulting primarily from gravity waves that promulgate into the stratosphere are difficult to resolve and predict. These motions are of lesser importance for this discussion.

Higher latitude winds are almost exclusively the result of pressure gradient forces and coriolis acceleration. "Geostrophic wind" is the term used to describe this motion, and it provides an analytical tool for obtaining global wind data from standard meteorological charts. Geostrophic winds are parallel to the pressure contour lines that are shown on charts, and the speed is related to the pressure gradient and latitude. Analysis of the synoptic pressure data is the best way to get a graphical "snapshot" of global wind conditions at a point in time.

An air particle has angular momentum as the result of "spin" imparted by the rotating earth. The angular momentum varies with latitude and, as illustrated in Figure 5.4A, there is no coriolis acceleration at the equator. If an air particle is accelerated by a pressure

gradient force to a low pressure area as in 5.4B, its angular momentum must be preserved, and the particle is deflected to the right by the apparent force, coriolis, which acts to preserve the angular momentum. As it speeds up toward the low pressure, coriolis increases until it reaches equilibrium as shown in 5.4C. The resulting wind speed is proportional to the pressure gradient and inversely proportional to latitude. Strong pressure gradients, where contour lines are close together, produce strong winds. In the northern hemisphere, the direction will be counterclockwise around a low pressure (cyclone) area and clockwise around a high. The reverse is true in the southern hemisphere.

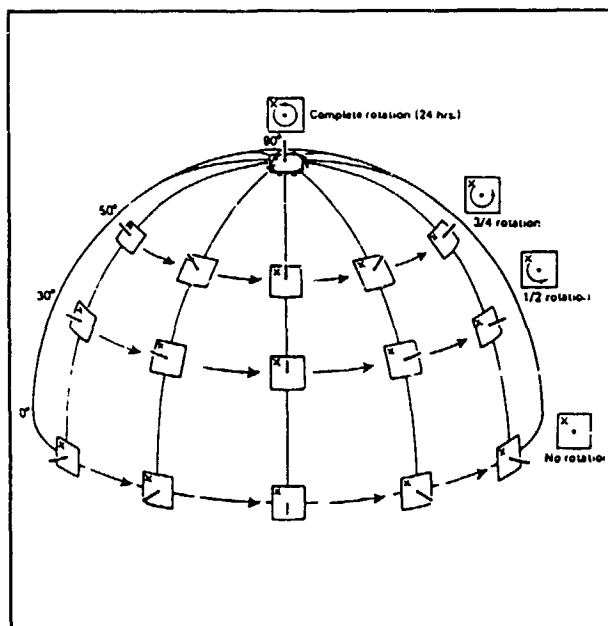


Figure 5.4A Illustration of the amount of rotation about the vertical axis at various latitudes in a 24-hour period.

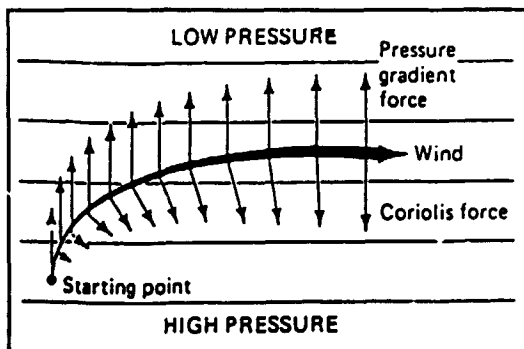


Figure 5.4B The Coriolis torque deflects the wind until pressure gradient and coriolis force are exactly balanced.

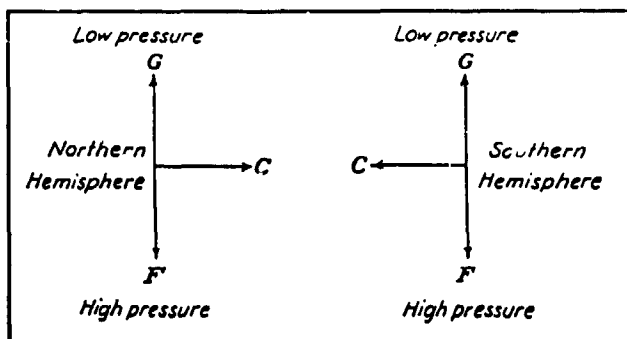


Figure 5.4C Geostrophic balance in the Northern and Southern Hemispheres.

Charts of global pressure distributions, depicted as geopotential height contours as illustrated in Figure 5.5A, are standard meteorological products. They are compiled daily for conditions as of 1200 GMT and distributed via established networks. Below 10 mb, wind speed is plotted as "wind barbs". Charts for 5 mb and above are not widely distributed at this time but can be obtained if needed. Meteorological data is presented on charts which use standard intervals and scaled so that the gradient can be measured in a convenient form to allow for easy computation of geostrophic wind. Figure 5.5B is an example of a nomogram used to compute 5 mb wind speed. To use the nomogram, transfer the distance between two standard height levels depicted in the chart in figure 5.5A to the nomogram in figure 5.5B and read across the curved line to the wind speed. The Geostrophic wind

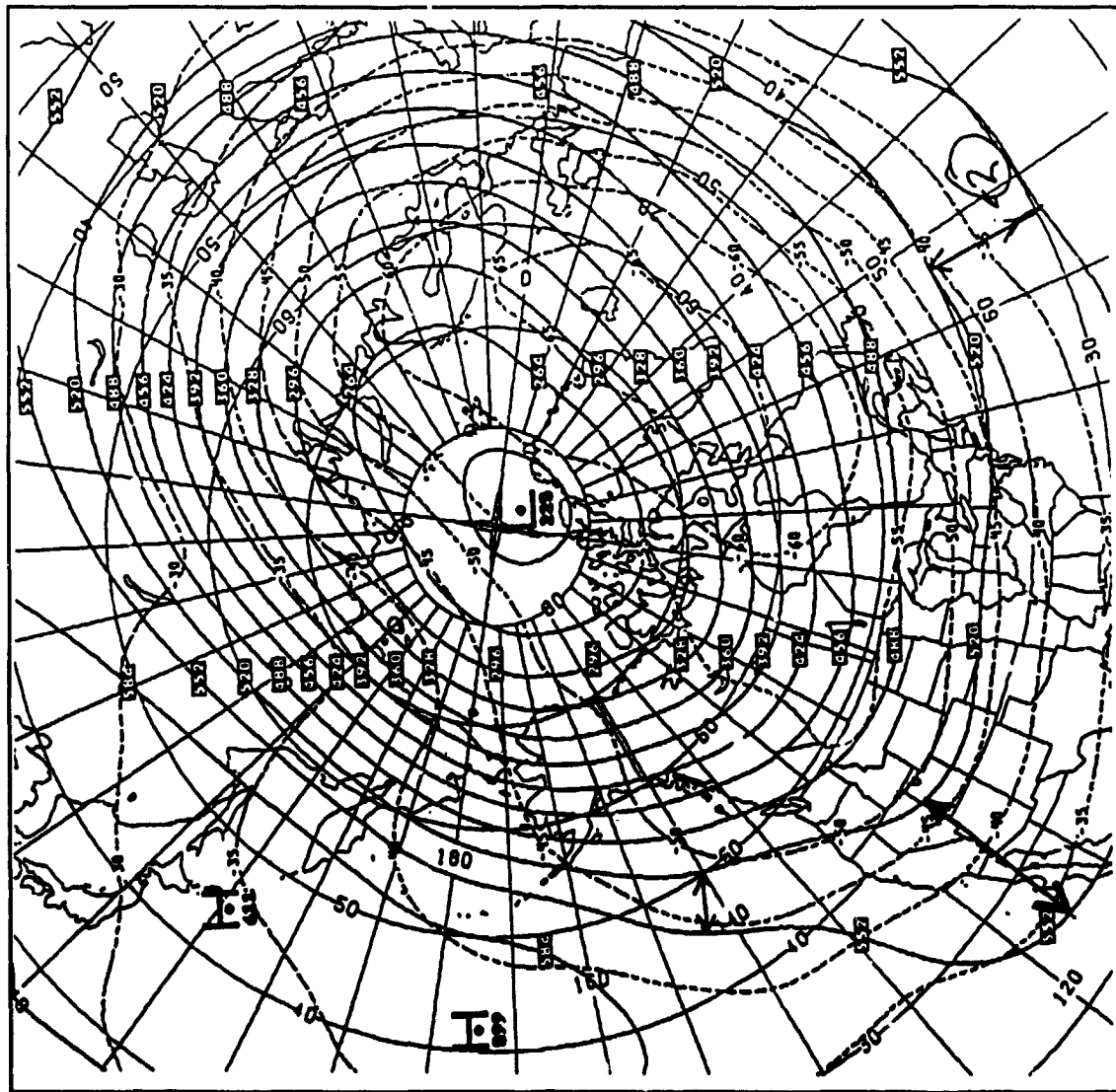


Figure 5.5A 5 mb level chart for January 4, 1989.

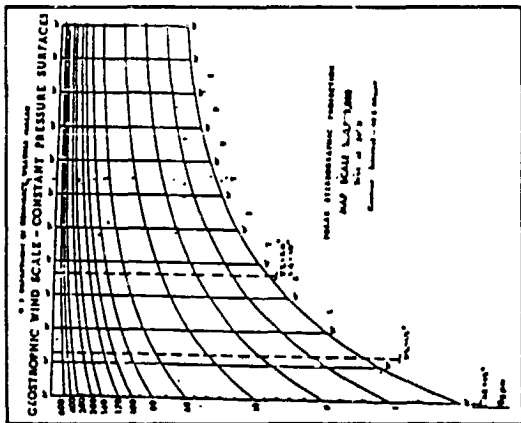


Figure 5.5B Geostrophic wind nomogram used for computing magnitude. The left scale is nautical miles per hour and the vertical scale is latitude.

WIND MAGNITUDE		
LOCATION	LATITUDE	SPEED
1	350N	45Kts
2	350N	35Kts
3	450N	70Kts

Table 5.2. Wind magnitudes computed using the above nomograph and the chart at the left.

direction is parallel to the height contours.

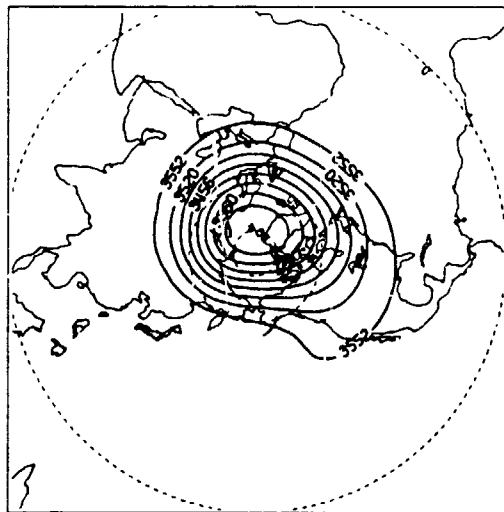
There are two factors that modify ideal geostrophic wind. They are surface friction and centripetal force. Generally, friction is ignored above 2000 feet altitude and centrifugal acceleration acts to decrease the wind speed only when the radius of curvature is small. Normally, these conditions do not apply in the stratosphere.

The geostrophic wind assumption allow us to look at global scale patterns in terms of readily available data. Eight-year-average pressure-height, wind and temperature were compiled by Nagatani, et. al., reference 9, at the National Meteorological Center. Figure 5.6A-D illustrate the trend in the northern and southern hemisphere. Using the geostrophic wind assumption, the charts provide a very useful way to visualize the overall wind patterns; but, because of the highly averaged nature of the data, variability is averaged out. The charts do not show the stability and predictability of these winds. Nevertheless, study of these charts provides a visualization of the general characteristics of circulation at the 5 mb level. It is useful to examine the circulation cycle to understand the basic patterns that exist in the stratosphere.

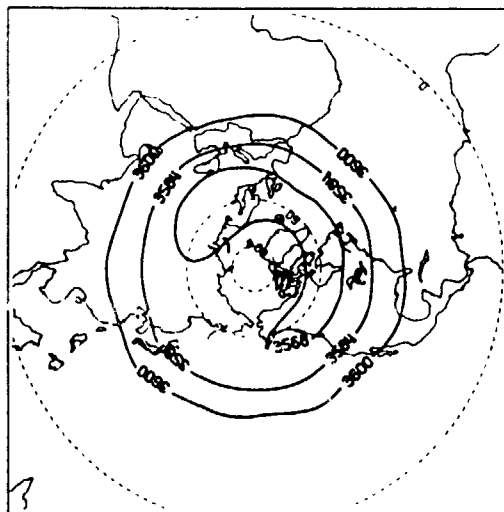
There are five general cases associated with the higher latitude circulation. They are stable winter pattern, stable summer pattern, northern hemisphere winter pattern, and southern and northern hemisphere transitions between winter and summer. Of all of the cases, the most interesting case is the northern hemisphere in winter because it has the highest variability from year to year. On average every other winter, we have a highly distorted situation which is referred to in the literature as a major, or sudden winter warming.

In the northern hemisphere, Figure 5.6A the cycle starts in November, while in the southern hemisphere it starts in May with a mature polar vortex located over the south pole. Winds travel clockwise around the low in the northern hemisphere. As winter progresses, the intensity of the polar vortex increases, as indicated by tighter spacing between the constant height lines which indicates higher pressure gradient and higher winds. This is particularly noticeable in the southern hemisphere, figure 5.6B. The southern hemisphere remains very stable, but the northern hemisphere polar vortex becomes distorted and unstable as the winter continues. By February, we observe an egg-shaped vortex, as opposed to a smooth, circular vortex. This distortion is caused by a high pressure area which normally exists in the northern hemisphere and is located just south of the Aleutian Islands and is called the Aleutian High. The summer months in both hemispheres, June through September in the northern Hemisphere and December through March in the southern hemisphere, are characterized by much smaller pressure gradients and, consequently, much lighter winds flowing in opposite directions.

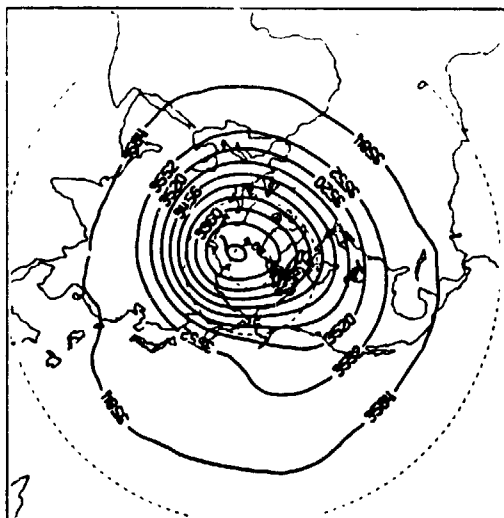
The transitional seasons, spring and fall result from the changing temperature patterns. In the spring the transition starts in the immediate extratropical areas, 20 to 30 degrees from the equator. A ridge (circle of high pressure centers) forms and begins to gain structure. As the season progress, the structure gains a more identifiable form and begins to move poleward until it eventually dominates the polar structure. The fall cycle starts in



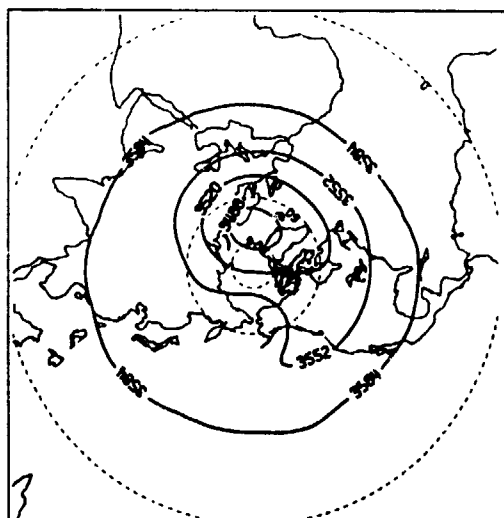
JANUARY



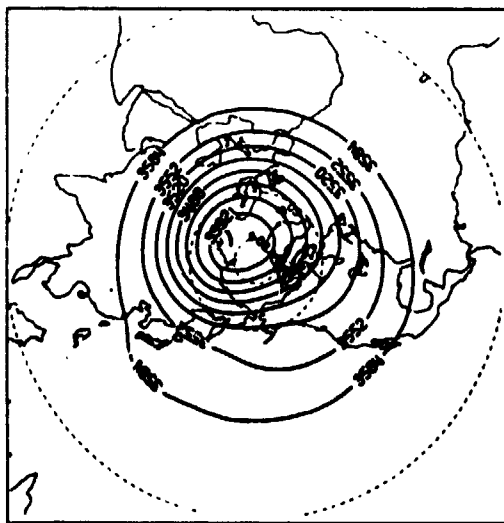
APRIL



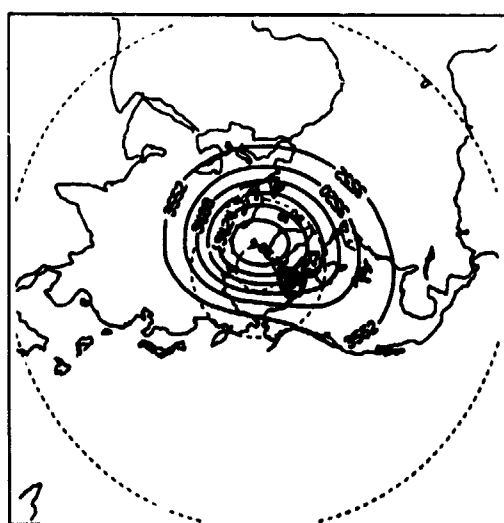
DECEMBER



MARCH

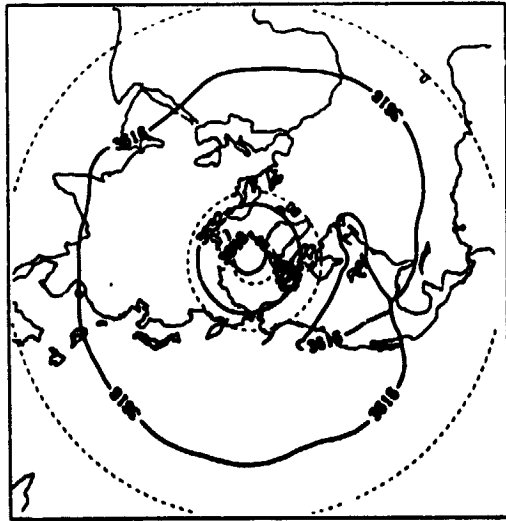


NOVEMBER

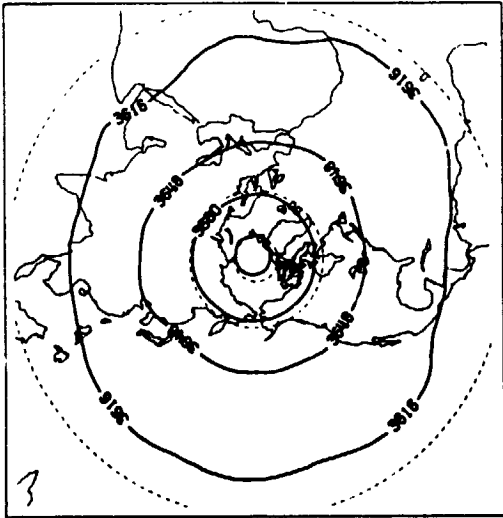


FEBRUARY

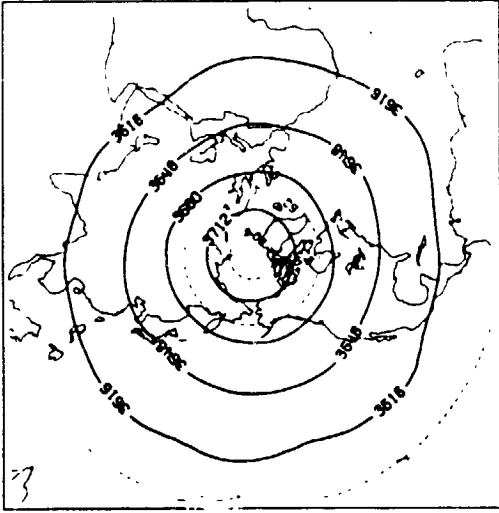
Figure 5.64 Northern Hemisphere eight year average 5 mb heights.

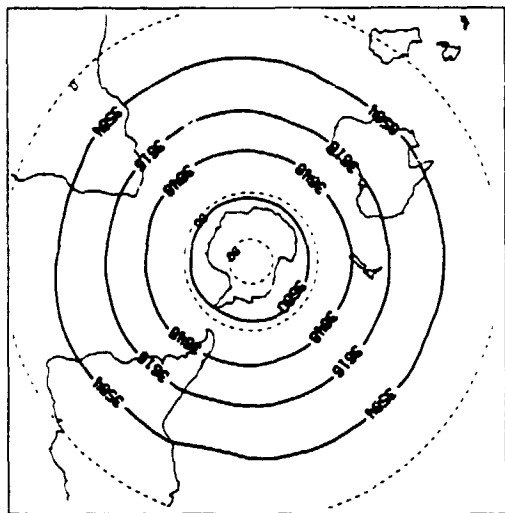


MAY

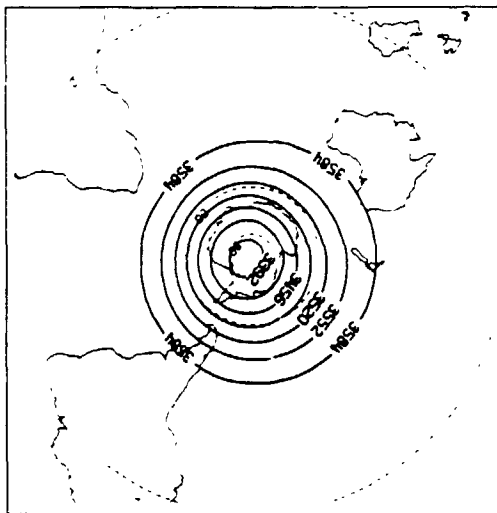


JUNE

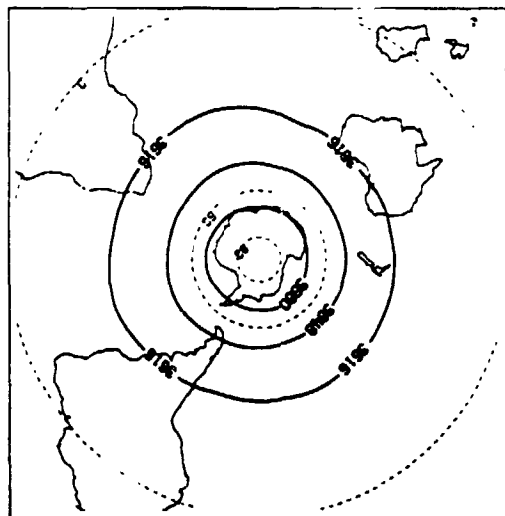




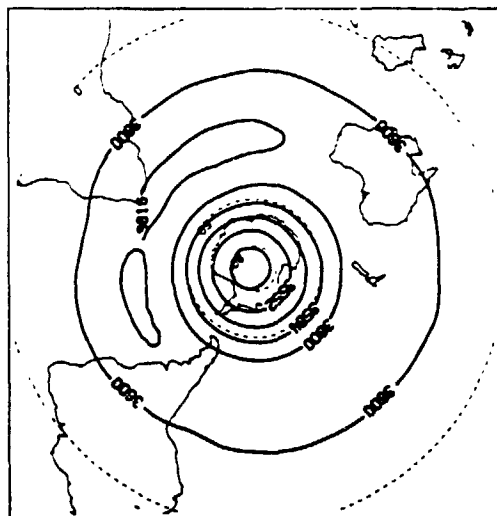
JANUARY



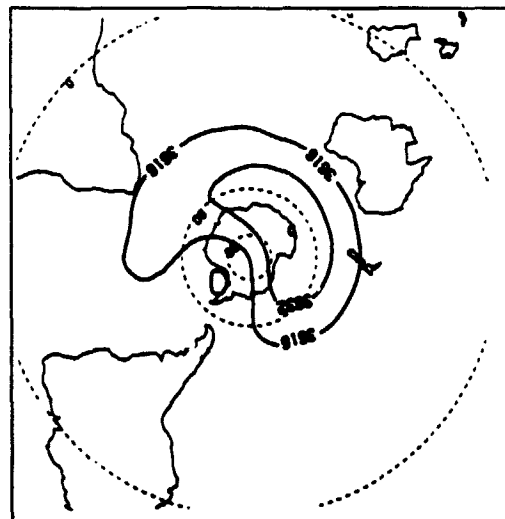
APRIL



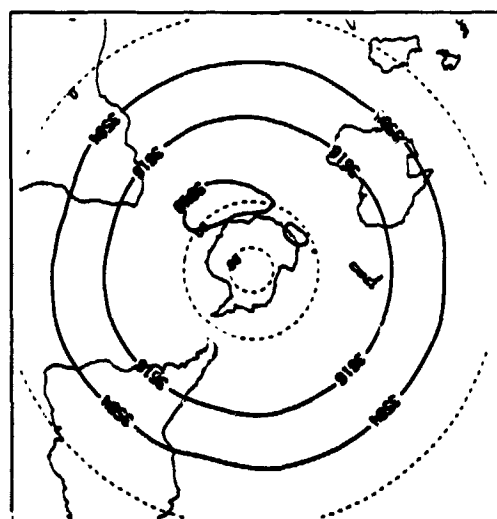
DECEMBER



MARCH

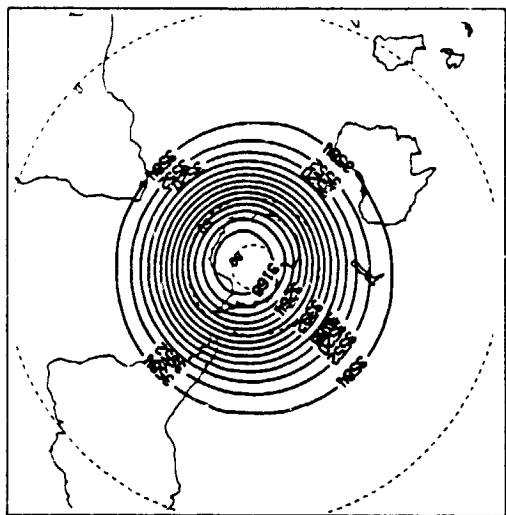


NOVEMBER

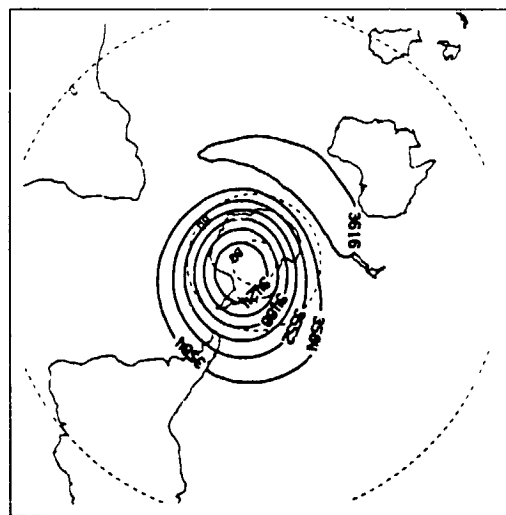


FEBRUARY

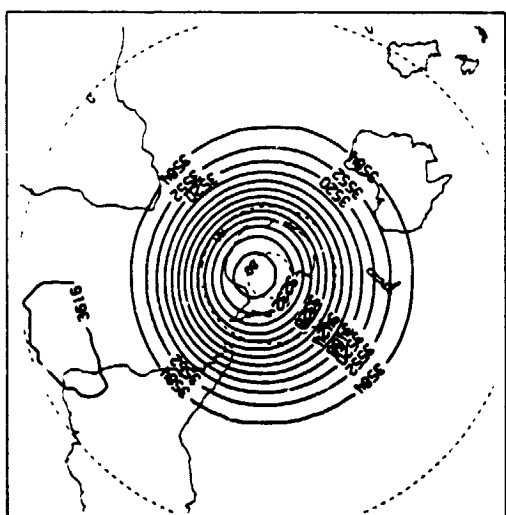
Figure 5.6C Southern hemisphere eight year average 5 mb heights.



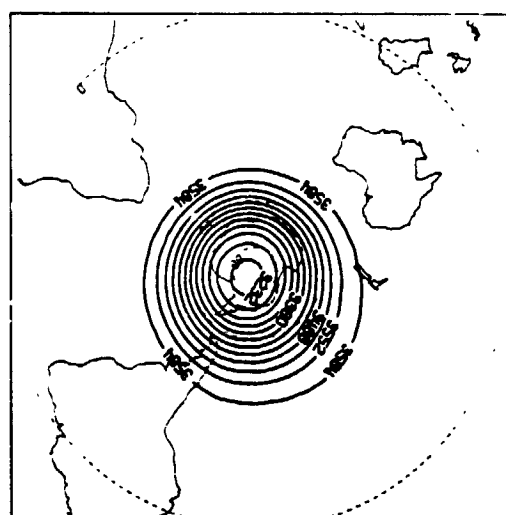
JULY



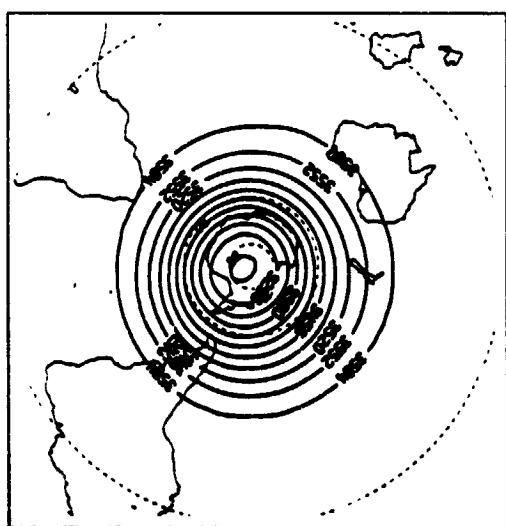
OCTOBER



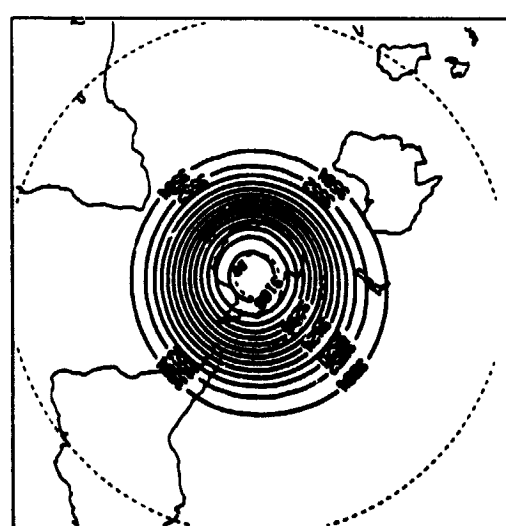
JUNE



SEPTEMBER



MAY



AUGUST

Figure 5.6D Southern hemisphere eight year average 5 mb heights.

the polar areas when the high pressure area develops a "bumpy" character with many small alternating high and low centers. The low areas develop structure and move equatorward. In the next section, we describe an example in which we are able to observe these transitions.

To summarize, the northern hemisphere winters from November to February are characterized by a low pressure area centered at or near the pole which is distorted occasionally by a high pressure area in the northern Pacific. The resulting flow is circular in the early part of the winter and then becomes egg-shaped later in the winter. Winds flow counterclockwise around this pattern or from the west to the east. These winds are referred to as "westerlies". During the summer, the northern hemisphere pole is dominated by a high pressure area and light gradients. The high pressure area causes winds to flow in a clockwise direction so that the winds are from east to west or "easterlies". These easterlies are typically much lighter than the winter westerlies. They are also circular and do not have the distortions common in winter.

Balloons do not fly in "average winds". Instead, the conditions at a specific place and time are governed by the overall state and time scales of change within the stratosphere. The patterns that have just been described are the result of highly averaged data. The obvious question is the amount of variability within the data. Temperature exhibits a similar amount of variability as does wind. Variance in temperature with the season and latitude is available from Nagatani, reference 9 and is plotted in Figure 5.7. The data plot shows that the variance in temperature increases significantly during the winter months in both hemispheres and peaks in the mid-latitudes. From this, one observes that winds during the winter months in both hemispheres are considerably more variable than winds during the summer months. Stratospheric wind is usually characterized in terms of time invariant Gaussian statistics (mean and variances). Empirical

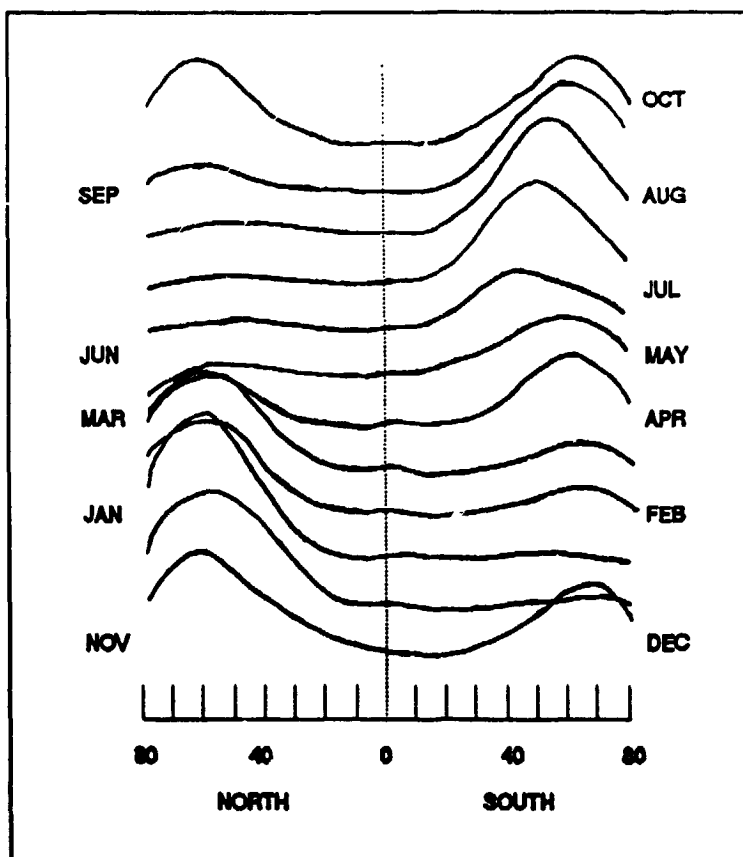


Figure 5.7 Global variance in temperature at the 5 mb level. Note that the variance increases in the winter. Temperature variability is closely linked to wind variability.

data bases exist which allow for the mean and deviation value of a wind vector to be determined for a place and time on the globe, but the time correlation is not easily available.

The series of charts in figure 5.6 is an excellent visualization tool for understanding wind patterns and circulation patterns in the upper latitudes of both hemispheres. Using the charts, one immediately gains a visual picture of the typical wind patterns which exist in the higher latitudes of both hemispheres. With some familiarity in long-term global circulation, we now examine the specific wind patterns which existed during 1989 and 1990 when the superpressure stratospheric vehicle was being flown. During this period of time, synoptic data were collected and will be described for illustration.

5.2.1 An Annual Circulation Cycle Example: Figures 5.8 A-M illustrate the annual changes in stratospheric circulation pattern as they exist at the 5mb (approx. 120,000 feet) level. Heights are shown on the charts in dekameters (10's of meters) with the leading 3 omitted. For example, 35,520 meters is shown as 552.

In early January, the stratospheric winds are westerly, travelling from west to east. We can see in Figure 5.8A that on January 1 we have a typical, well established, polar vortex and counterclockwise circulation with winds along lines of constant latitude. During January, we begin to observe warm air being drawn from the tropics to the polar areas. This warming can be intense and on January 15, 1990, the northern hemisphere pole reached a temperature of +10 degrees centigrade at 5 mb. In 1989, we experienced temperatures of 0 degrees centigrade above 60 degrees north. Corresponding to the warm poleward flow, we see an anti-cyclone (high pressure area) developing over the northern Pacific centered just south of the Aleutian Islands.

In Figure 5.8B, we see that the Aleutian high has intensified to the point that it has distorted the normal, constant-latitude, cyclonic flow. We note that winds across the United States are from the northwest, as opposed to being from the west. We would expect trajectories during this part of the year to be headed in a southeasterly direction from the launch point. The velocities are normally 30 to 40 knots. This pattern persists and intensifies through February. In figure 5.8C we see that high pressure has replaced the normal wintertime low. Over the United States and Canada, flow is dominated by the anti-cyclone and winds have shifted from the west to the east, trajectories would have a heading of 270 degrees. This is a complete flow reversal and wind reversal from what is normal for this time of the year. 1990 was more intense than most in the dominance of the high pressure area.

Return to cyclonic flow starts from the upper part of the stratosphere and moves down. We first observed the return at the 2 millibar level, where, in 1990, we saw cyclonic flow and westerly winds by late February. In 1990, westerlies never returned below the 20 to 30 millibar level. As we will see later in the actual balloon flight of 1990, our vehicle was trapped in this flow reversal at about the 30 millibar level.

In late March, figure 5.8E, cyclonic flow has resumed in the northern hemisphere, and from latitudes 30 degrees north and above, we have smooth, westerly flow. By mid April, figure 5.8F, we would observe high pressure forming between 20 and 30 degrees latitude.

As the Spring continues, the high pressure areas form a ring of high pressure areas called a ridge line. In Figure 5.8G we see the ridge line is passing over the United States late in April. As the ridge line passes over a point on the ground, a change of winds from westerly to easterly is observed and, as the center of the ridge passes over, the wind in the stratosphere is almost stagnant. This phenomenon has been called the spring turnaround by balloonist because after the stagnation period, the wind will be reversed and from east to west. This is a favorite time for scientific experiments to be flown because balloons launched into these conditions will remain overhead in a general area for an extended period of time.

During this period, we observe that the polar vortex intensity has diminished and is being "filled in". For example, the first of April, we might expect the height of the 5mb level at the pole to be about 35 kilometers. By mid to late April, the height of the 5mb level at the pole is about 35.2 kilometers. By early May, the height of the 5mb level has reached about 36 kilometers, and the pole has a relatively high pressure. By the end of May, figure 5.12H, the high pressure dominates the pole and the northern hemisphere. Winds are easterly through the entire northern hemisphere above 20 degrees north. This pattern remains very stable with the high pressure area intensifying throughout the year, reaching heights of 37 kilometers. Winds during this period of time are light, typically 20 knots. Additionally, the trajectory patterns remain very close to constant latitude circles.

The summer pattern is very stable but by the end of August, figure 5.8I, the 5mb pressure surface is becoming "bumpy" and one observes areas of alternating high and low pressure with only a small amount of difference between peaks. Soon we begin to observe a ridge line forming 50 degrees north with a persistent lower pressure and cooler temperature area centered at the pole as in Figure 5.8J. This, of course, is a relatively low pressure because, at this point, this low pressure over the poles is well above 36 kilometers.

About the middle of September, figure 5.8K, the ridge line has progressed below 40 degrees north, and the ridge line is passing through the United States, causing the second stagnation period, or another turnaround. North of the ridge line, winds are tending to be westerly, while south of the ridge line, winds are tending to be easterly. In both cases, winds are quite light and somewhat more variable than before. In these very light wind conditions, an observation on a particular day is highly dependent on the exact position of each of the relative highs and lows. The small saddlebacks or minor highs and lows are being formed. The resulting winds modulated by these patterns cause the winds to be more variable.

In September, structure has clearly formed over the poles, figure 5.8K, and there is a dominance of the cyclonic flow. Additionally, the pressure gradients are much stronger than they were during the summer period. The resulting winds following the geostrophic wind requirements are much higher. At latitudes below the well-structured pattern, we still are experiencing light and highly variable winds, making trajectory planning very difficult. By early October, the height of the 5mb level at the poles has decreased to well below 35 kilometers. Figure 5.8L for November 1st shows that the complete winter cyclonic structure has returned to the 5mb stratosphere and winds are westerly. From now through the end of the year the polar vortex will continue to intensify, reaching maximum intensity (minimum

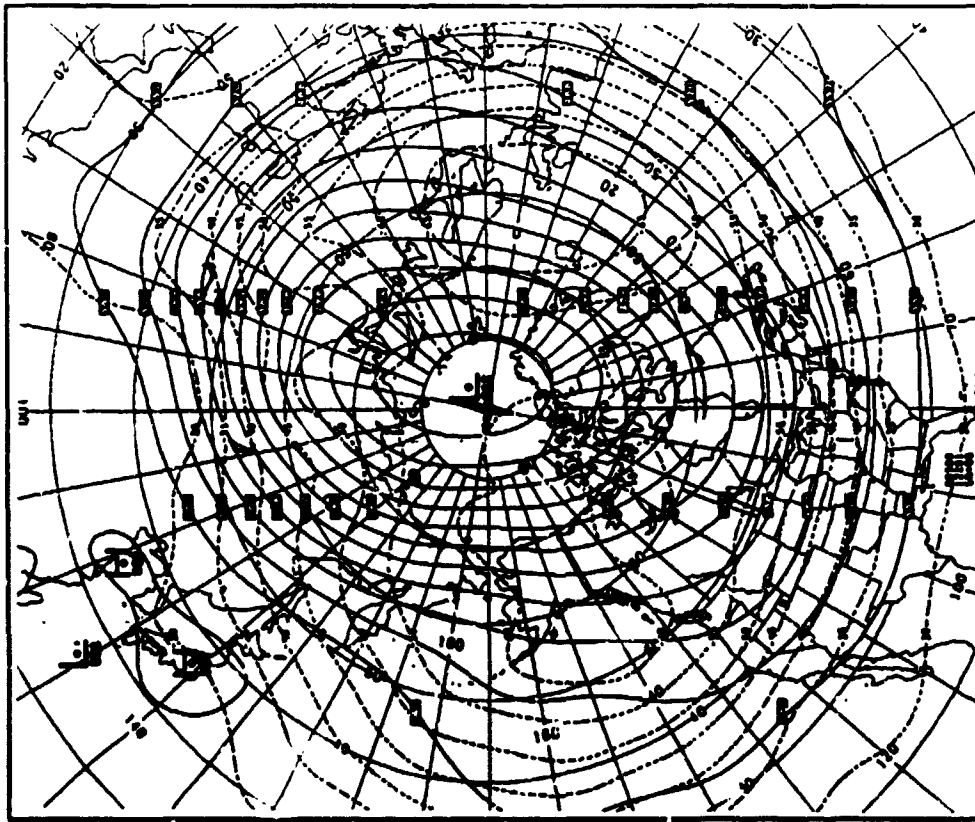


Figure 5.8A January 1, the polar vortex has a well-defined quasicyclonic structure. Winds are flowing counterclockwise from west to east at about 50 kts.

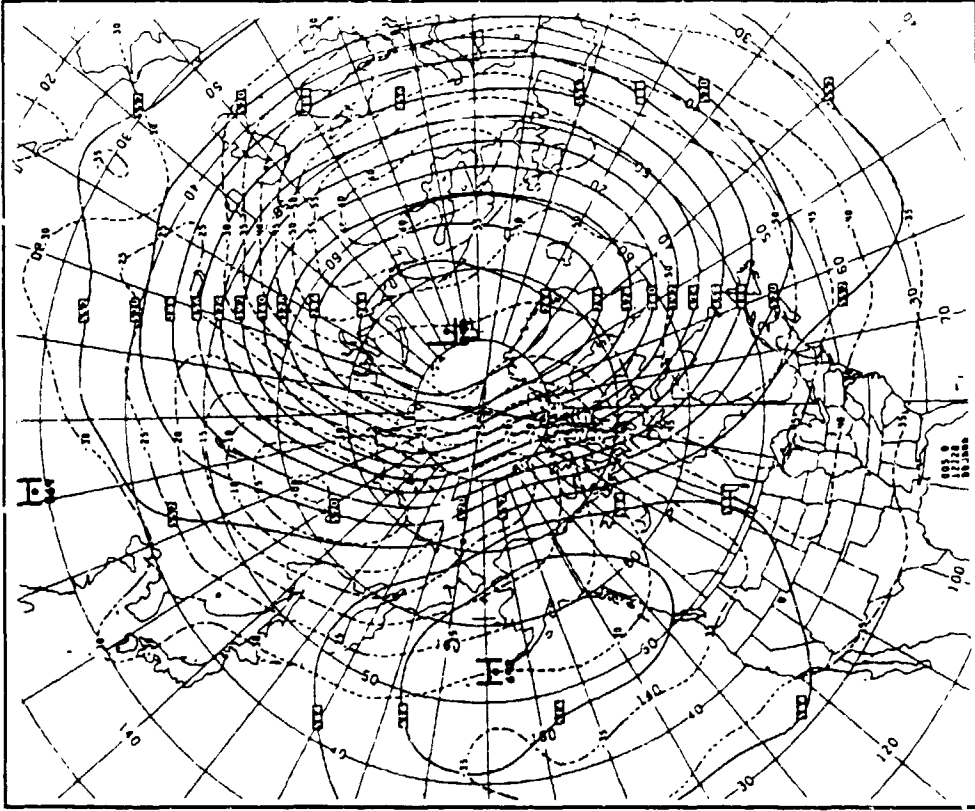
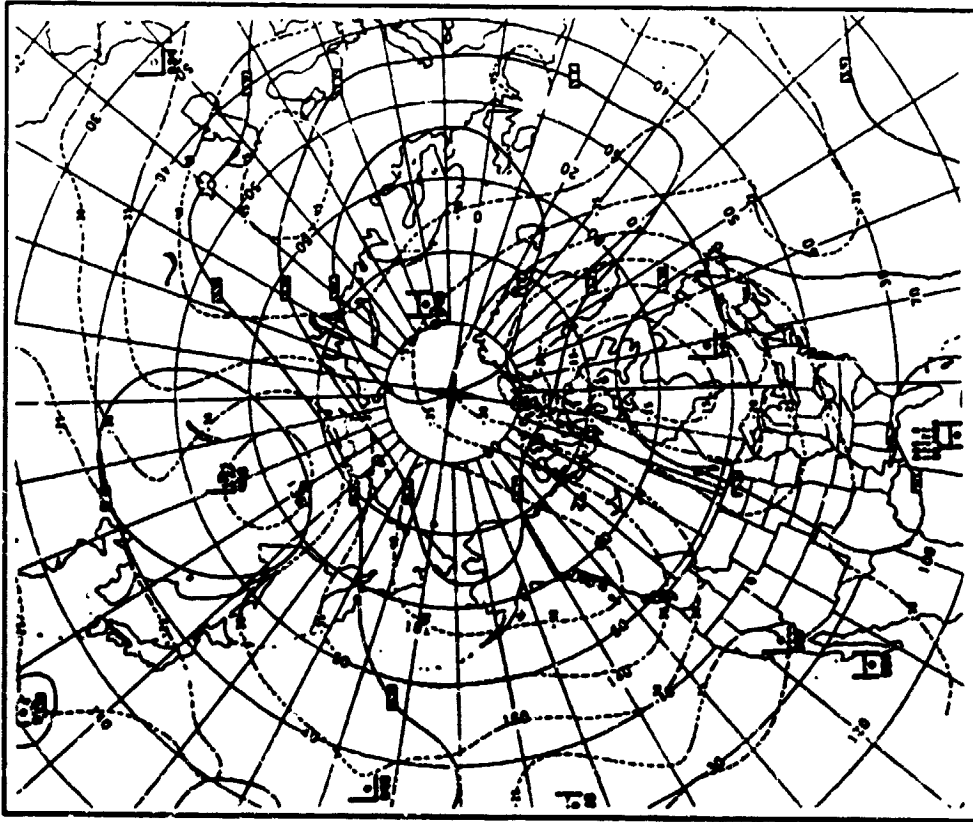
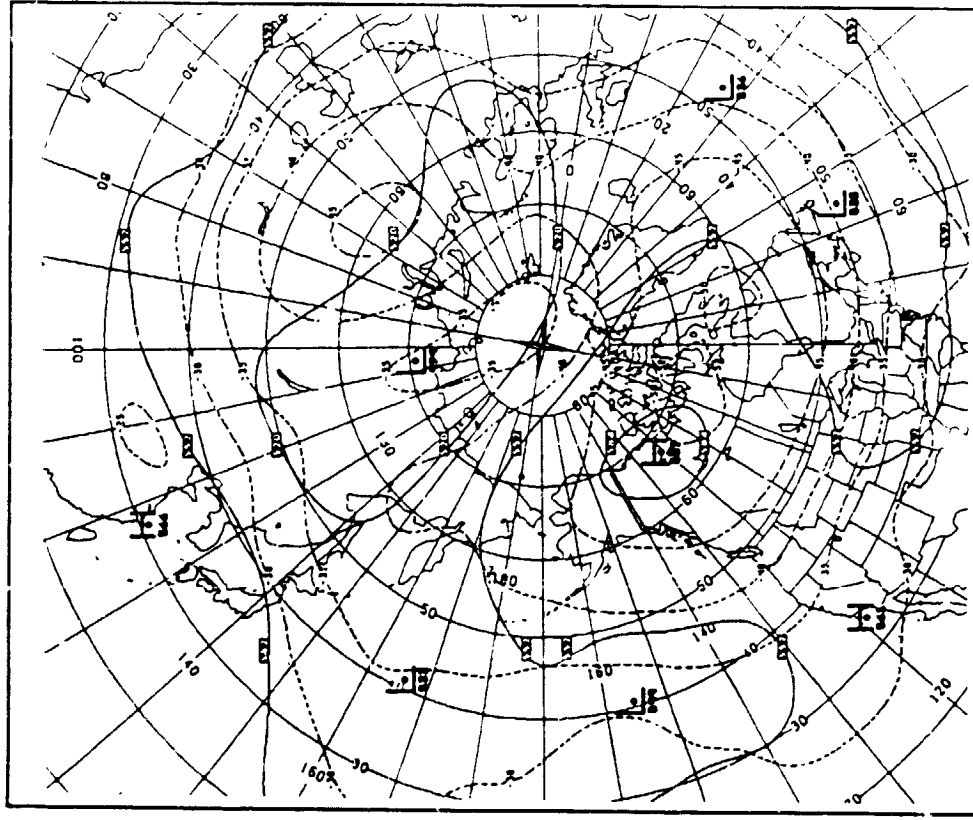


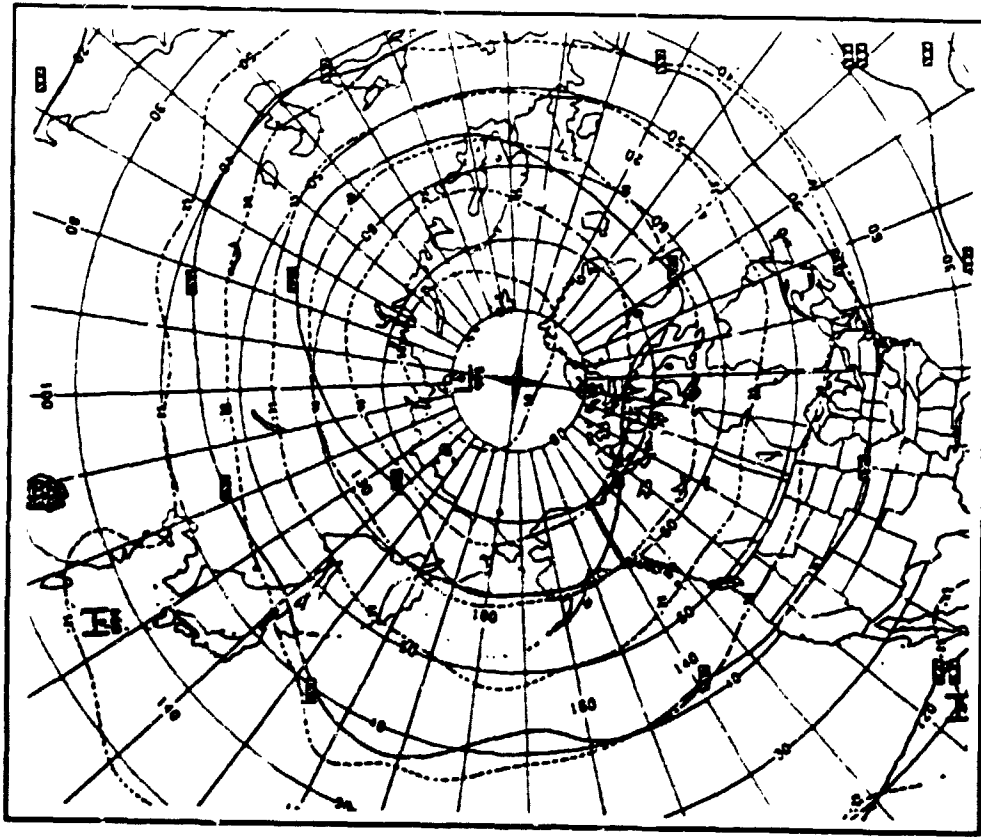
Figure 5.3B January 28 The pole has become warmer, a high pressure area has developed over the Pacific which perturbs circulation in that half of the hemisphere.



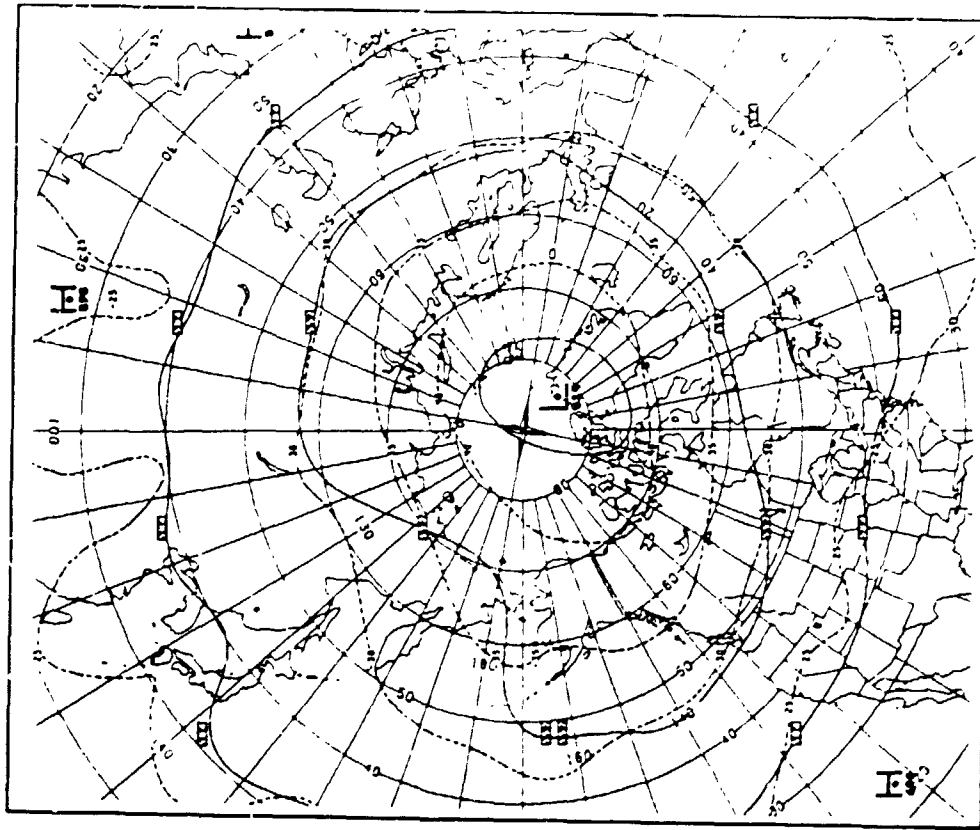
5.8C February 22 High pressure dominates the pole and the warm air center has moved. In some years, summer-like anti-cyclonic pattern exists for a brief time and winds reverse to easterly at the higher latitudes.



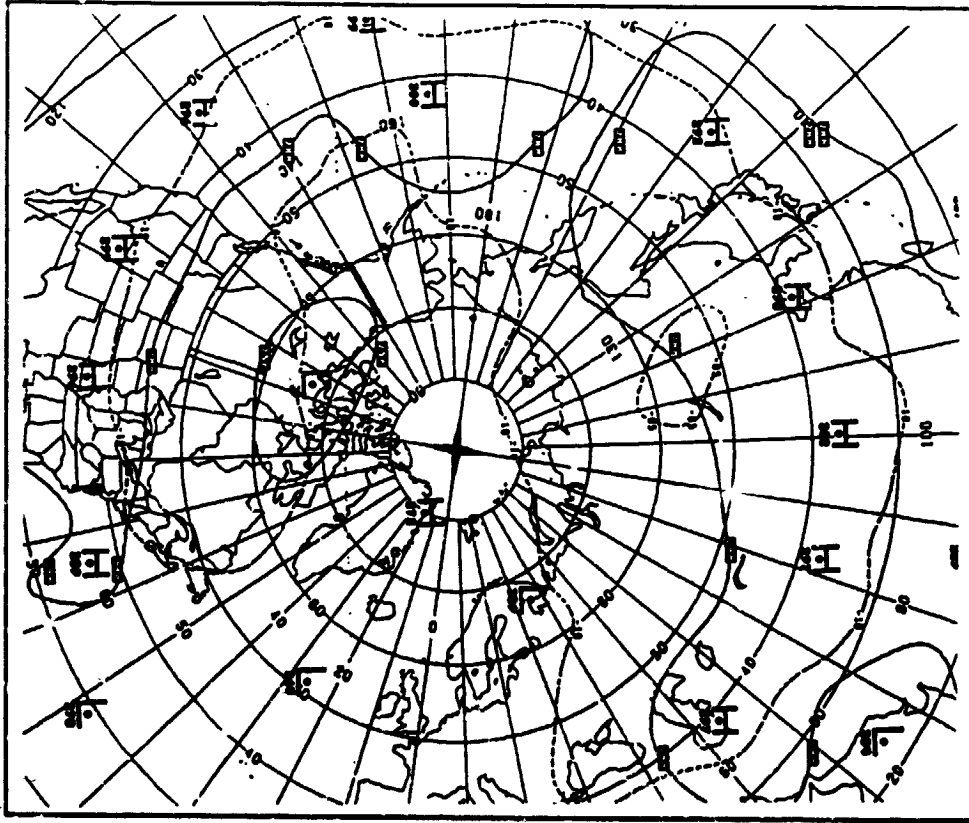
5.8D March 1 The breakup of the winter warming is difficult to forecast. Here, the low pressure is beginning to re-form at the pole.



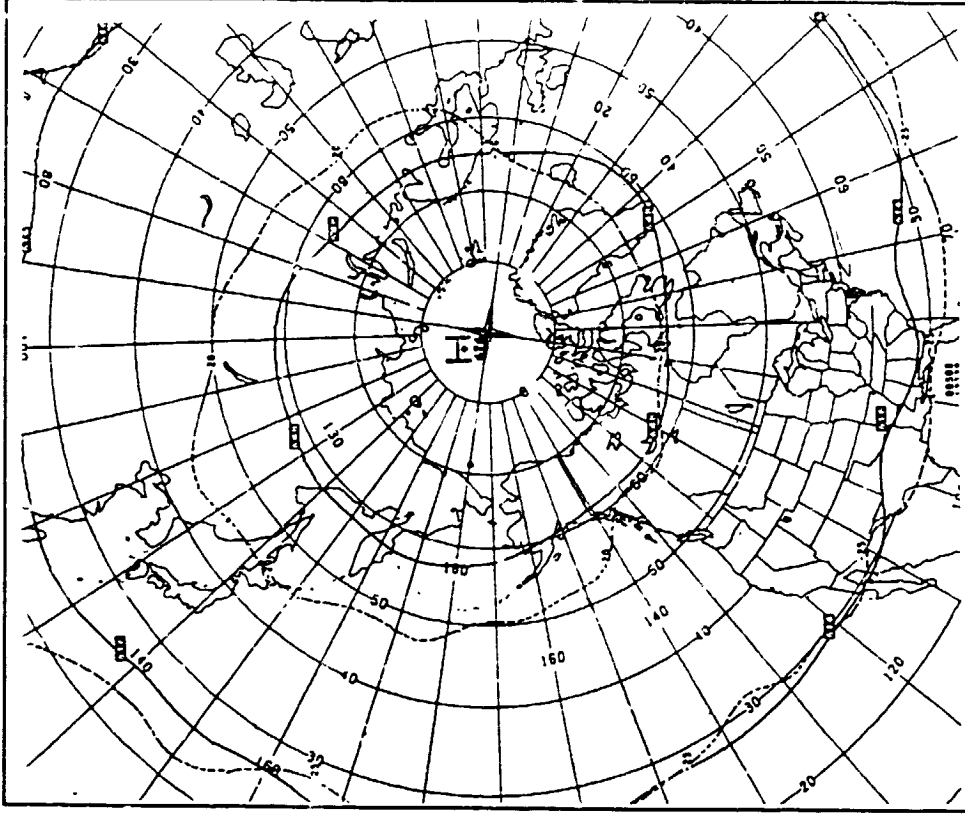
5.8E March 29 During March, the polar vortex was eventually reestablished and circulation was again counterclockwise around the pole.



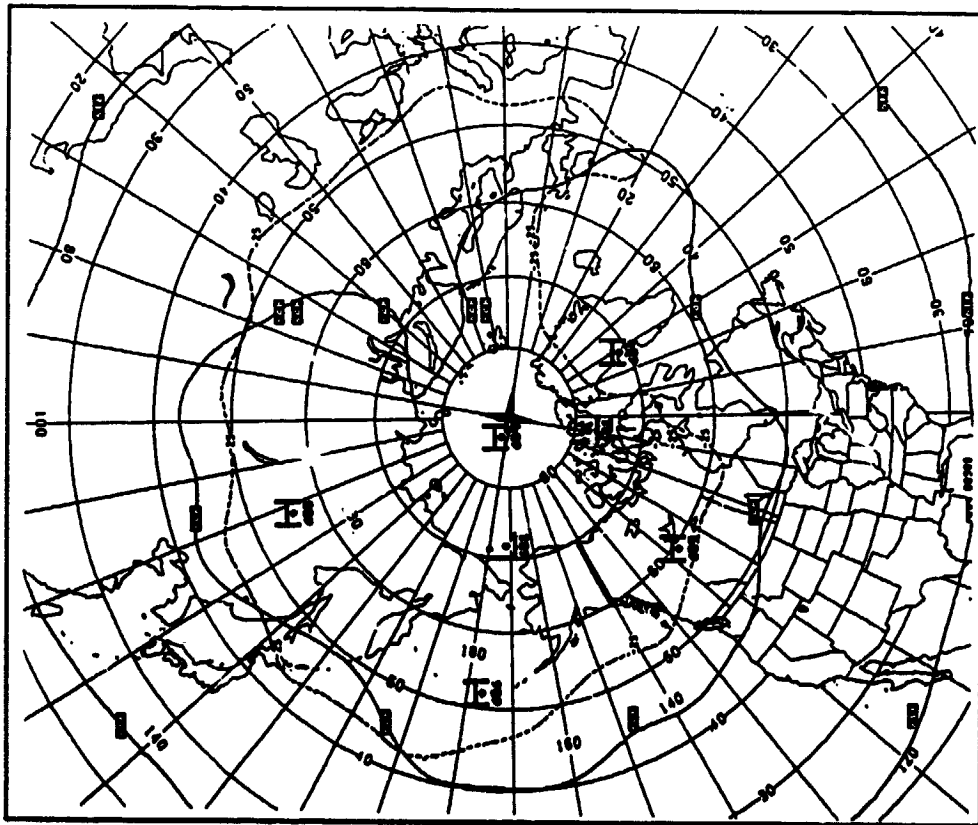
5.8F April 13 The spring transition starts with the formation of a "ring" of localized high pressure areas at lower latitudes.



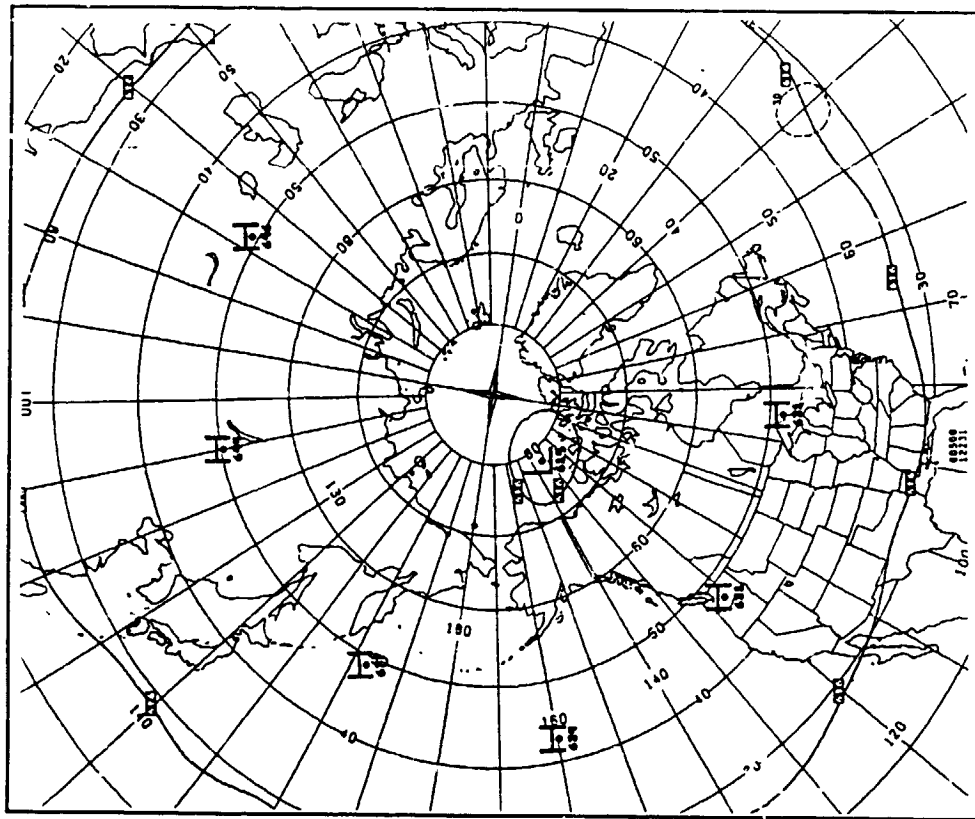
5.8G April 30 The high pressure areas begin to gain structure and move northward, forming a ring or ridge line around the globe.



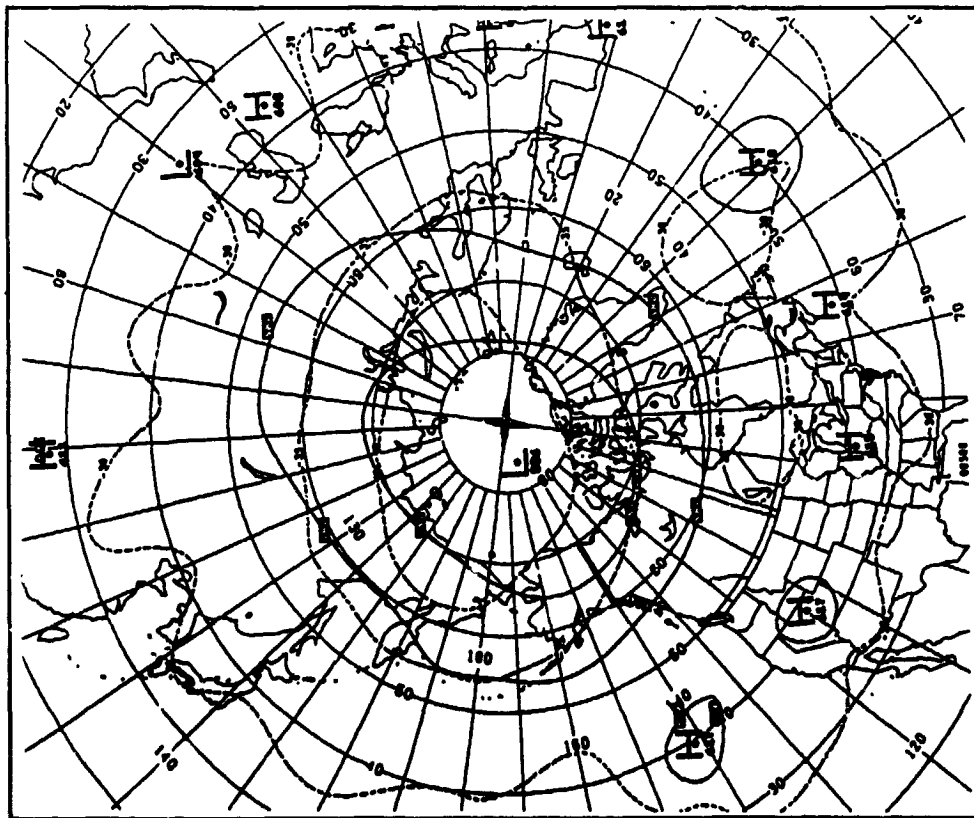
5.8H May 28 During May, the high pressure structure dominates the pole and the entire hemisphere. Winds are now light and clockwise around the pole. This pattern will remain almost unchanged until August.



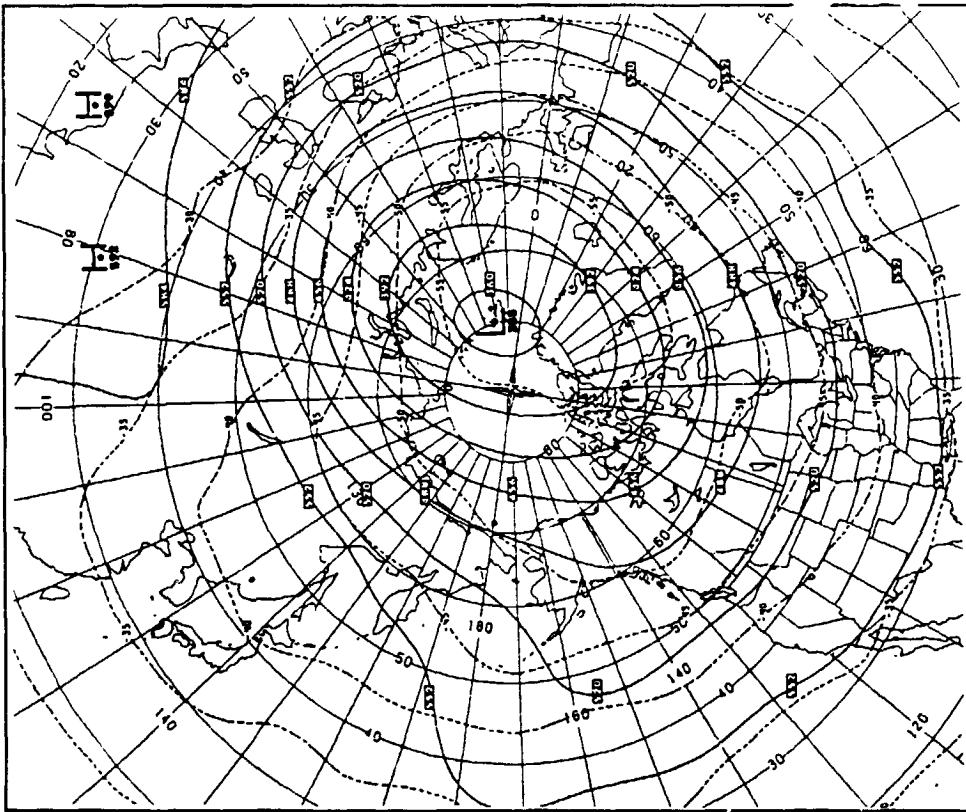
5.8I August 24 As the polar area begins to cool, the smooth pressure structure that existed earlier begins to become irregular.



5.8J August 31 By the end of August, low pressure is becoming dominant and a ridge line of high pressure centers is moving away from the pole. Circulation around the low is again counterclockwise.



5.8K September 21 As fall continues, low pressure dominates the pole and circulation becomes counterclockwise. The polar temperature has cooled 25°C since summer.



5.8L November 1 The winter pattern is well established by November. Polar temperatures are about -55°C and will remain at that level until spring except during the midwinter warming.

height) below 32 kilometers.

This discussion of a typical yearly cycle should be compared to the average data described earlier in Figures 5.6. Averaging over long period of time and displaying the data on a monthly basis, as shown, fail to illustrate the highly variable nature of the stratosphere, particularly during the transition seasons. Despite the fact that a typical year does not look exactly like an average year, the pattern is relatively constant. The primary variable is the intensity of the mid-winter warming and the exact timing of both the warmings and the transitions. The sudden warming phenomenon is a very interesting case. Because our interest is largely in operations in the northern hemisphere, a discussion of this phenomenon is appropriate.

5.2.2 Sudden Warmings: During the northern hemisphere winter, the characteristic zonal mean configuration is dramatically disturbed by the transport of warm air to the polar regions in a short period of time. Polar stratospheric temperatures increase rapidly with time, and, on occasion, there is a complete reversal of the zonal winds to an easterly direction. On average once every other winter, this event is significant enough to be labeled a "sudden" or "major" warming. To the meteorologists, it is referred to as a major warming if at 10 mb or below the zonal mean temperature increases poleward from 60° latitude and the zonal mean wind reverses. If a major warming occurs sufficiently late in the winter, the westerly polar vortex may not be restored before the normal seasonal circulation reversal occurs. Winds will remain easterly from the warming through the spring and summer.

The warming is first observed by a raising temperature in the Aleutians area. The phenomenon begins in the troposphere and promulgates upward into the stratosphere. This corresponds to the growth of the large high pressure area over the Aleutians and northern Pacific. The geostrophic winds associated with the normal cyclonic pattern over the poles become highly distorted. Under some conditions, upper transfer of energy is blocked by the rapid formation of an easterly flow pattern. This easterly flow tends to damp continued acceleration and growth of the midwinter warming. When that happens, the progress of the unstable warming is cut off and the warming is classified as minor a warming. In general, minor warmings will occur at least once a year but are followed by a quick return to the normal winter circulation. There are varying opinions about the exact nature of the dynamics of the sudden warming. However, sudden warmings are fundamentally generated by the promulgation of energy from the troposphere by planetary long waves. Since the phenomenon is only observed in the northern hemisphere, it is logical to conclude that the topography-forced waves are responsible for the vertical energy transport. The southern hemisphere, with a relatively small mass at midlatitudes, produces much smaller amplitude-stationary planetary waves.

In the year during and preceding the flight tests of the superpressure stratospheric vehicle, we experienced major winter warmings and the occurrence of the warming during the year of the actual flight tests was a concern. The program had been planned for a transcontinental flight to be launched from the west coast. A winter warming which reversed that flow pattern would have had serious negative effects. Fortunately, the sudden warming

of 1990 reestablished the classical westerly flow prior to the actual test flight.

5.2.3 Equatorial Circulations: In the tropics, the solar radiation is far more constant than it is at higher latitudes. Extratropical circulation, as discussed earlier, is the result of pressure gradients which, in turn, are the result of changing solar radiation which results in equatorial antisymmetric temperature fields. The equatorial middle atmosphere below 35 kilometers (5mb) is characterized by a long-term oscillation that is not directly linked with the seasons and is called the quasi-biannual oscillation or QBO. Its period is somewhat irregular but averages 27 months. In other words, in one year the winds are in one direction and the next year they are in the other direction. Higher in the stratosphere well above 35 kilometers, the seasonal variation is characterized primarily by a semiannual oscillation or SAO of the mean zonal winds. The net result is that in the tropics below 10 millibars, winds are well characterized by the QBO phenomenon and wind speeds of about 20 kts. Above the 10 millibar level, one encounters a mixture of the quasi-biannual oscillation and semiannual oscillation. Above the normal balloon operating areas, the winds are dominated by the semiannual variation. It is best, therefore, to describe each of the two oscillation patterns separately.

Figure 5.9 illustrates the characteristic of the QBO at 10 mb. The amplitude of the oscillation is nearly constant from about 40 mb up to 10 millibars. It decreases rapidly below 50 mb. The changes in the phenomena promulgate downward at the rate of about one kilometer per month, which means that, in general, the observed change in the quasi-biannual phase is first seen at high altitudes, and its change is predictable at the rate of one kilometer in height per month. While the QBO is not exactly a two-year oscillation, there is a tendency for the phase reversal to occur during the northern hemisphere summer. For our purposes, the primary interest is that circulation patterns below 10 millibars are biannual in nature; that there is very little meridional flow, that is, there is very little north-south flow; and that the maximum amplitude of the winds are within about 20 knots. Additionally, the phase reversal of the quasi-biannual oscillation can be predicted by observing the upper part of the stratosphere.

While the QBO has been studied quite extensively, the second phenomenon, the semiannual oscillation, SAO, is not as well understood. The problem encountered in studying the semiannual oscillation is that data are far more difficult to obtain. The base altitude of semiannual oscillation is above the five millibar level, and all analysis must be deduced from a very few number of rocket sounding data and limited satellite data. Fortunately, the maximum amplitude of the semiannual oscillation occurs well outside of the normal operating range of balloons. The region between 10 millibars and about two millibars is between both the quasi-biannual oscillation and the semiannual oscillation and is influenced by both phenomena. Figure 5.10 illustrates the effect of the superposition of both effects.

To summarize the equatorial flow, below 10 millibars the winds are relatively predictable and changes occur in time scales of about two years. As we move above the 10 millibar level, we observe a quasi-biannual oscillation with a superimposed semiannual

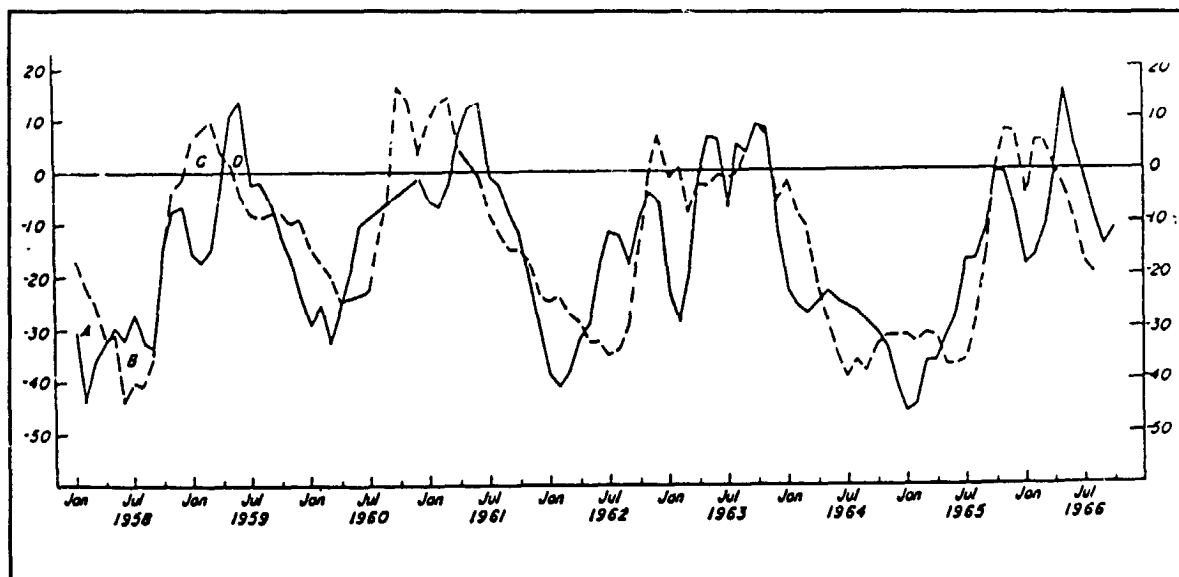


Figure 5.9 Monthly averaged zonal winds (m/sec.) at 10 mb for Balboa C.Z and Ascension Island. Positive winds are from the west.

oscillation. The semiannual oscillation in turn promulgates downward from the mesosphere, and these changes are observable from above. Finally, we note by observation that winds have very low meridional components, that is, north-south components, and that the general amplitude is generally less than 30 knots.

5.3. Trajectories: The mobility needs of various missions can be summarized into three types of long-term trajectories patterns: quasi-orbits, homogenized distribution and precision overflights. Short-duration missions using zero pressure balloons rely on the minimum wind zone for earth synchronous missions. While this is an important military mission, its discussion is beyond the scope of this report. 120,000 feet or 5 mb, was chosen as the baseline altitude for LDFFF because of the general belief that the flight trajectories at this altitude would be more stable and predictable.

The most stressing trajectory is the precision overflight required by surveillance imaging applications. We assume that this mission requires a nadir to 45° view of the target.

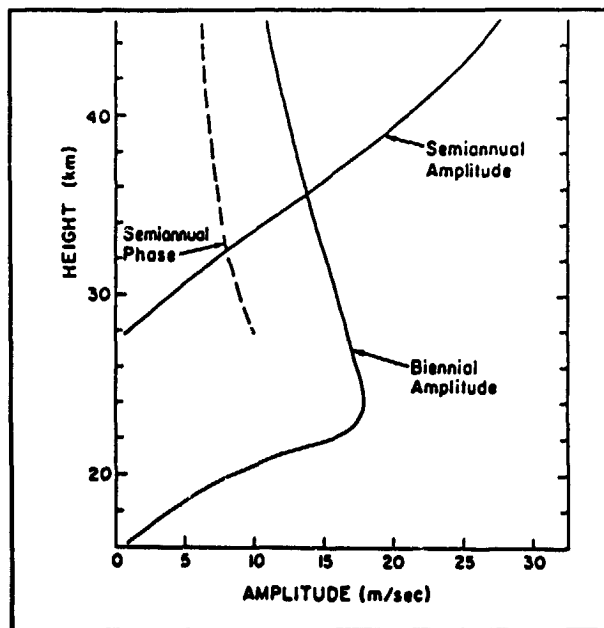


Figure 5.10 Amplitude of the quasi-biennial and semiannual, equatorial oscillations as a function of height. Note that at 35 km (approx 5 mb) both effects are equally prominent.

This in turn requires that the vehicle pass within 20 miles of the target. The total margin of directional error in track course prediction over a 1200-mile flight must be within one degree, including the ascent errors. We know that small-scale perturbations exist, but they are not characterized or easily observed except by a long-duration balloon. Errors in the ascent can be limited by height, temperature, and wind sounding prior to flight. Assuming that a ship is the launch platform, mobility in launch location is available, and overflights of about two days and around 1000 miles may be possible.

The quasi-orbital trajectories are considerably less stressing than imaging overflights. In quasi-orbits the user requires that the balloons operate in a band which passes over the same general area on each global circumnavigation. The issue is the long-term stability and positioning of these orbital bands. An example is the Arctic call-back mission that was proposed to DARPA as one of the first balloon missions. Here, the requirement was to maintain a general path around the pole and provide signal intercept receivers for ships in the polar region. Another example is connectivity in a latitude band where overflights of a theater area are required on multiple passes. There is a concern that the orbit will not be maintained after the seasonal changes or for more than one orbit. We would expect that the equatorial areas can support an orbital trajectory except during the QBO phase change.

The homogeneous distributions are the least stressing trajectory requirement. In this case, the entire hemisphere is covered randomly with balloons which provide an "umbrella" around the entire hemisphere. The fundamental concern is that there could be areas where the balloons are attracted and held for long periods. Equally important are areas of very high-speed winds where balloons pass very quickly making these areas scarcely covered relative to other areas. Fortunately, the areas of very high winds near the poles are of little interest. The relative wind speeds around the globe determine the distributions of balloons. Individual missions allow the balloons to be launched or reseeded in areas of highest need.

Coleman Research conducted a Phase I SBIR program in which they simulated a one-year flight using statically averaged data. This method of compiling the winds leaves questions about the interpretation of the results because the wind vectors used in the simulation apparently did not consider the time scales of change at the flight altitude of 5 mb. Nevertheless, the results support the concept that there is no tendency for balloons to "get stuck" in areas like the poles. The balloons drifted around the hemisphere on seasonally predictable tracks but there was no apparent pattern.

5.4 Models: Models for stratospheric trajectories allow the operator to project into the future the position of a balloon at a particular altitude. The value of the model is a function of both the amount of observed data which have been incorporated into the model and the length of time that the model attempts to extrapolate the trajectory. An ideal model would allow the military user to input his trajectory requirements, and the model would determine the launch point and flight path that can be expected. For balloons, the model must describe motion on a constant density plane. It also requires that a model make maximum use of current observed data.

In designing a model, we can compile past data or simulate the physical processes

that are occurring. Historical data can provide mean and variance of the winds for all locations and times of the year. We could also treat stratospheric movements as a Markov process where the initial state, the observation, and a transition function are obtained from historical data. Lastly, we can attempt to simulate the atmospheric dynamics. In this case, modeling becomes computationally intensive and requires detailed understanding of atmospheric physics. For military applications, we might want a time-invariant statistical model for general planning and a Markov-type model, with actual observations, to conduct the particular mission. The ideal model would operate in either a climate or forecast mode.

Conceptually, the simplest model would be geostrophic wind profiles. Pressure gradients are plotted on a daily basis throughout the entire stratosphere, up to 0.2 millibars. They represent the best of the observed data available from satellites. As shown earlier, using the geostrophic wind model, we obtain essentially a snapshot for trajectories for a particular time over the entire globe. Given careful analysis of these data and experience in plotting charts, it is possible to extend the predictions of the pressure gradient temperature fields out at least five to ten days. This is particularly true during stable summer and winter periods.

The geostrophic wind model is easily available and is fairly easy to use. Additionally, it provides for visualization of the trajectories. Unfortunately, the geostrophic wind model requires relatively high-pressure gradients in order to produce predictions of geostrophic wind. Also, the satellite data is poorly resolved, and there are known to be smaller scale phenomena which cannot be seen by satellite distort geostrophic wind fields.

A way to model stratospheric trajectories is to move from one point to the next and use a data base of expected winds at that place and time to get winds for the next time interval. This discrete step approach was used to model a one-year-long trajectory for the long-duration balloon project at DARPA. The simulation used NASA's Global Reference Atmosphere Model (GRAM) (ref11) to obtain winds. GRAM is an empirical FORTRAN computer simulation of the earth's atmosphere developed by Georgia Tech. Reference A summarizes the capabilities and operation of GRAM. The features which are most significant are that GRAM provides a worldwide, 12-month data base. Winds are provided in statistical form (mean values and standard deviations from the mean) and represent actual data collected over several decades.

SKIHI is the general circulation model that currently provides the most complete representation of the physics of the middle atmosphere. The model includes topography, realistic distributions of continents and oceans. Predicted fields include wind and temperature. Radiative heating and cooling is computed using diurnally averaged solar isolation. Figure 5.11 from reference 12 shows the breakup of the polar vortex during the warming of 1979. As can be seen, the model extended reasonably well out to ten days. In part B of the figure, we see the same prediction using two different resolution sizes. The courser resolution failed to accurately predict the details of the pattern. Additionally, Mechoso attributed differences to poor tropospheric forecasts. It appears that a requirement for forecasting a global level phenomenon like a sudden warming, requires a high level of resolution and good forecasts of the tropospheric conditions. Another model

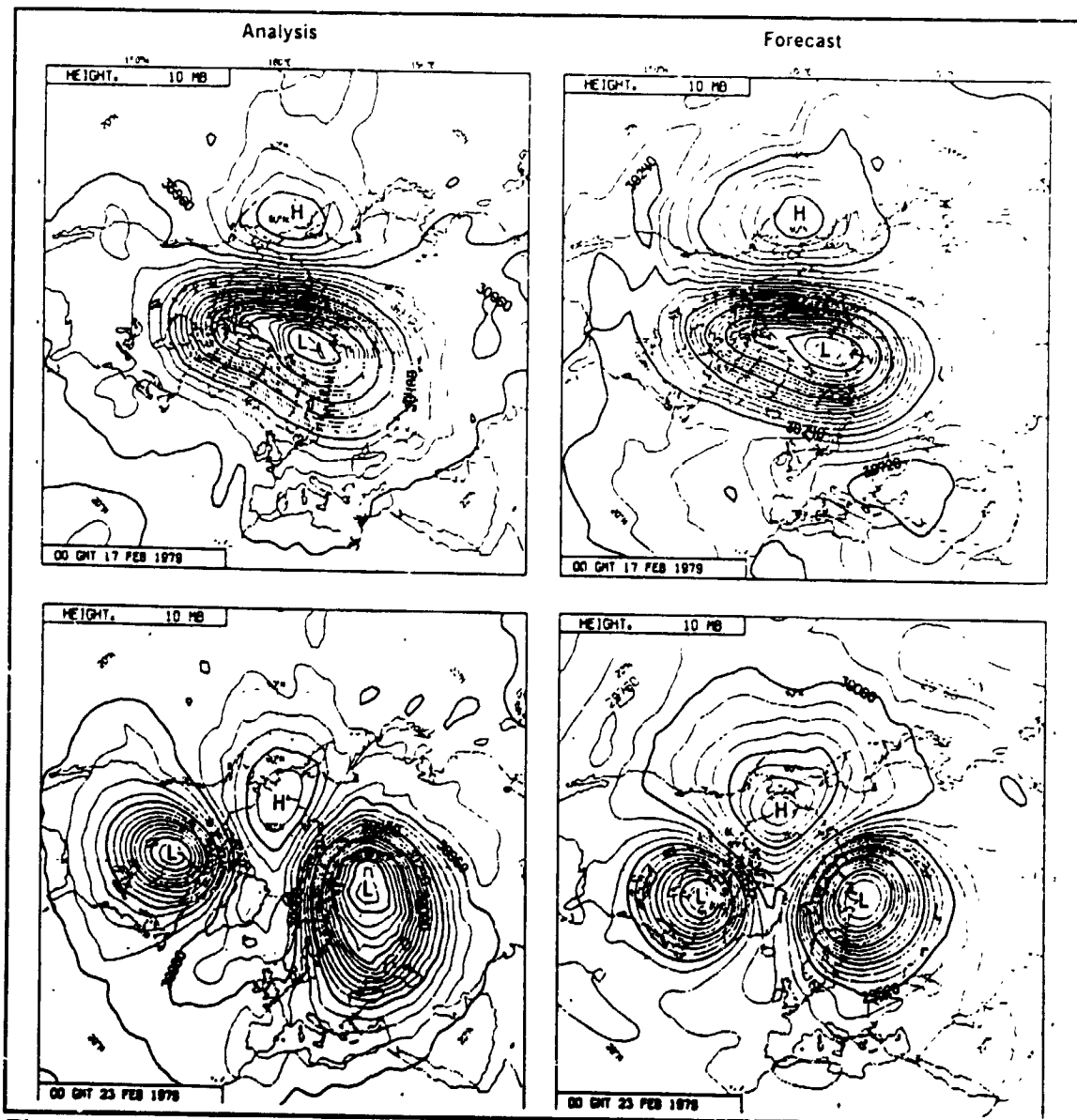


Figure 5.11 10 mb heights comparing four and ten day forecasts. Left figures are the actual analysis and the right figures are the forecasts. The four day forecast is at the top.

is the Global Circulation Model developed at the United Kingdom Meteorological Office. The European Center for Medium Range Weather Forecasts (ECMWF) is an operational forecasting model which extends to 10 mb. It has been used for forecasting key events, such as winter warmings.

Several dynamic and chemical tracers are commonly used in stratospheric modeling. Contours of constant tracer value are plotted and allow the user to visualize motion in areas where wind measurements are not available. The use of such contours in the diagnostics of large-scale transport in the stratosphere has proven to be effective, even in areas with fairly low pressure gradients, also, in areas during seasonal transitions. Commonly used tracers are Ertel's potential vorticity, quasi-geostrophic potential vorticity ozone and other chemical

species. Another mechanism for determining the large-scale motions of the stratosphere are to use trace elements which are naturally occurring in the stratosphere and observe their movement. The chemical species have been found to act as reasonably good tracers for the dynamics of the stratosphere. They have lifetimes which are at the same order or longer than the dynamic changes which are occurring in the stratosphere and have been found to tag airflow and to help in understanding and developing models of the stratosphere.

Potential vorticity is considered to be an excellent tracer for stratospheric dynamics and has time scales of several days. Lines of constant potential vorticity become material lines in which the contours comprise the same as the fluid particles. Ertel's potential vorticity is among the most widely used dynamic tracers. It is plotted on constant entropy surfaces. The surface of most interest and often used is the 850-degree Calvin isotrope (850 K) which occurs around the 35 kilometer level. Another tracer which has been used by meteorologists in very similar potential vorticity is the quasi-geostrophic potential vorticity or Q_g . This quantity is conserved following geostrophic motion on isentropic surfaces. Q_g is perhaps a better tracer of a constant density profile because Ertel's potential vorticity assumes advection by a three-dimensional flow process. Unfortunately, large scale plots of quasi-geostrophic potential vorticity are not as available at this time as are plots of Ertel's potential vorticity on a constant isentropic surface. Nonconservative forces acting in the stratosphere, such as friction or gravity wave drag, result in nonisentropic conditions which will eventually deteriorate dynamic tracers. Contours of constant potential vorticity may be the only source of reasonably accurate trajectories under some conditions.

6.0 PROGRAM DEVELOPMENT

In this section we propose a continuation of the SSV program. The original intention of this project was to demonstrate a superpressure capability and validate basic engineering models. The two remaining NASA flights will gain some engineering data but the limited flight experience will raise many additional questions and there were many engineering issues that were beyond the scope of the project. In order to develop a viable military balloon capability the three areas listed below require additional research:

1. **Engineering Science.** The design models for a balloon vehicle, flight dynamics and subsystem must be tested. Operational and reliability constraints must be established.
2. **Trajectory.** Flight trajectories models must be validated with actual flight data.
3. **Mission applications.** Tests of full systems and in military environments must be evaluated in order to determine strengths and weaknesses of balloon based concepts.

Engineering sciences entails all design elements of a total balloon based architecture. The thermodynamic models of the internal gas temperature, the performance of the balloon film in the flight environment, the ascent trajectory model and the float stability predictions were not tested. Natural frequency and aerodynamic damping in rotation and translation were not among the objectives of the first flight but this quantity must ultimately be understood in order to design long duration flight vehicles. These flight dynamics quantities are needed for antenna pointing systems and balloon stress modeling. The quality assurance and manufacturability of the vehicle was tested in a limited sense but additional testing is needed to gain reliability assessments.

Trajectory analysis and modeling will require extensive testing and modeling. Essentially no trajectory validation was accomplished during the flight. Additionally, there has been no systematic attempt to model the flight path of a Superpressure balloon in any past superpressure flights. The modeling of a constant density particle is a unique problem in atmospheric dynamics because these particles do not occur naturally. Application of conventional atmospheric tools is a now subject of conjecture. We believe that many platform-years at altitude will be required before trajectory predictions can be exploited to the limit allowed by nature.

Missions for balloon-base system will need to be flown and the relative value of the system must be measured against competing technologies. Cost was cited as a primary feature of a balloon system but until a prototype system can be tested the real value and cost of the system is difficult to evaluate and support from users will be difficult to obtain.

Flight experience in any military application is fundamental to establishing LDFFF as a viable capability. Ideally, a well defined, specific military requirement that needs a

balloon based architecture could be identified and a military agency would support the development and transition. We were not able to identify a single critical mission to focus a follow-on program on in the course of briefings and discussions. We found that users were unwilling to invest in system concepts that have not been demonstrated. Of the ideas briefed, theater level communications and atmospheric research projects generated the most interest either as a stand alone capability or as part of larger system. Either ,of these missions could provide an excellent overlay to a balloon architecture development.

6.1 OBJECTIVES

The following is a list of specific objectives that should be part of a follow-on program. These objectives are generalized to any military system and can be accomplished in a number of missions scenarios.

Vehicle Engineering:

1. Predict lifting gas supertemperature under varying environmental conditions.
2. Determine aerodynamic damping, stability derivatives and natural frequencies.
3. Accurately model float dynamics including float entry.
4. Characterize material and manufacturing flaws in terms of flight duration and mission reliability.
5. Establish acceptable tolerances for materials and processes.
6. Evaluate the effects of rain and ice on climb performance.

System Engineering:

1. Model payload thermal conditions.
2. Determine the accuracy of the antenna/sensor pointing ability.
3. Develop alternate lifting gas sources.
4. Measure atmospheric RF and optical attenuation at altitude.
5. Evaluate and flight test prime power sources.
6. Test balloon to balloon networking concepts.

Mobility:

1. Develop specialized atmospheric modeling tools for long duration constant density flight.
2. Validate flight path predictions with flight data.
3. Relate constant density surfaces to other meteorological phenomena.

Mission Applications:

1. Measure observables and determine vulnerability.
2. Determine packaging, handling and storage constraints for lifting gas in various environments.
3. Evaluate the total costs of a balloon-based system as compared to alternate vehicles.
4. Determine environmental limitations for balloon systems.
5. Reconcile the legal overflight issue.

6.2 PROJECT OUTLINE

A DARPA free floating flight program would ultimately provide a number of military users with a balloon architecture as an alternative to more conventional flight vehicles. There are a number of mission scenarios that could demonstrate an important military capability and at the same time mature balloon systems to a level that other users can exploit. A large area theater communications system is a good project for several reasons: it is generally needed as an enabling capability, the packet switched radio payload has been developed for another DARPA program, it presents a modest level of stress in the development flight systems and finally, it will require a lot of flying. The scenario will establish a rapidly constructed communications network across the Atlantic. Flights will be limited to the international airspace over the Atlantic to defer overflight issues. The network would serve Naval units afloat and ashore and provide connectivity for several weeks.

The program will include four major elements: balloon systems development including launch and recovery; payload modifications to include user interface; trajectory validation; antenna pointing and tracking. The balloon will be larger than flown in previous programs in order to carry the fifty pound payload that will be needed for the onboard systems. Military systems will require a robust "operator proof" launch system capable of operations world wide at remote sites. The packet radio was developed for DARPA by Hazeltine and is easily adapted to large area network communications. Trajectory prediction is important to all LDFFF missions. For communications, accurate trajectory prediction is needed for cost estimating, site planning and determining coverage statistics. Antenna pointing developed in this project is needed for a variety of applications including communication where wide band or covert transmissions are needed.

Another potential project is a global atmospheric survey. Observations of the dynamics, physics and chemistry of the middle stratosphere have new urgency stimulated by fears that human activity might adversely effect this delicate environment. In-situ measurements provide unique information that is unavailable by remote sensing. Conventional balloons and rocket soundings provide a vertical snapshot that is unable to resolve spatial and temporal characteristics. Additionally, soundings in remote areas and over the oceans are difficult and expensive. The system that will use many free floating superpressure balloon data "nodes" at various altitudes in the middle stratosphere. They will collect and relay in-situ measurements for periods of up to one year with high resolution that is available from GPS. It will provide researchers with a low cost source of unique data needed for stratospheric research. This program provides flight experience at a low cost that is applicable to military systems.

6.3 PROGRAM COST ESTIMATE Program costs can be divided into five categories:

1. **Flight Operations.** Conduct flights, recovery, long duration validation, interoperability and the major demonstration. 250K
2. **System Development.** Develop and test pointing & tracking, prime power, thermal control, balloon systems and material. 1000K.
3. **Adapting and testing packet radios.** Conduct ground, flight and interoperability

tests of the network. 300K

4. Balloon vehicles. Purchase ZPP's and SPP's for tests of subsystems and flight tests. Conduct research and tests of new vehicle and material concepts. 200K

5. Management and support DARPA agent costs and oversight be a government laboratory. Address legal aspects of the intended flights. 250K

Total project cost over two years: \$2000K

APPENDIX A

Brief History of Long Duration Balloon Developments

Long duration flight can be achieved using any of the three types of balloon described in section 5.1. One technique is to extend the life of a zero-pressure balloon by ballast or cryogenic replacement of the lifting gas. Another is the superpressure balloon. The third is the sky anchor concept. In 1970 National Scientific Balloon Facility, NSBF, started a program to develop a long duration capability. In 1976, Texas A&M developed the Sky Anchor concept with sponsorship from the National Science Foundation and NSBF. Several sky anchor flights were attempted but very few achieved any success. Despite several programs over the years all of these concepts were tried, but only the superpressure balloon has demonstrated reliable operation.

Several programs have demonstrated successful superpressure capability. The earliest attempt was by AFCRL in 1961. The flight lasted nine days at an altitude of 70,000 feet. The first operational flying was done by NCAR in the GHOST (Global Horizontal Sounding Technique) program which started in 1968 and continued through 1970. Over 200 balloons flew for extended periods at 100 mb and below with less than 100m of altitude deviation. Some flew for over a year with the longest being 744 days. The payload was 1/3 to 3/4 pounds.

In 1973 project Boomerang successfully circumnavigated the globe in the southern hemisphere with two, 64-foot, unreinforced polyester superpressure spheres. One flight lasted 36 days and was recovered within 10 miles of the launch point. The other lasted for 212 days. Both floated at 80,000 feet with about 100 pounds of payload. These early flights used a relatively thick film. By 1976 larger balloons were being tested but the film thickness was reduced to save weight. The thinner film proved to be unsuitable in the cold temperatures due to flaws and discontinuities. Other experiments included the French EOLE in 1972, the TWERLE in 1972-1975, Tropical constant level balloon in 1978, CBS (Carrier Balloon System) in 1975, and the EMP (Electromagnetics of the Middle Atmosphere) in 1983-84. All of this flight activity was conducted at less than 80,000 and most below 60,000 feet. With few exceptions there has not been any attempt to conduct flights of more than a few months or above around 80,000 feet.

Beginning in 1977, NSBF conducted a series of tests of Sky Anchors (SA) with the objective of carrying large payloads to 120,000 feet. The program encountered numerous launch problems but eventually achieved some successes. One system remained aloft for four days at 119,000 feet with 500 pounds of payload and another remained aloft with 1200 pounds payload for two days. Altitude excursions of around 4,000 was typical with as much as 20,000 feet were observed in the extreme cases.

APPENDIX B

SPP Design analysis

Analysis of the elements of superpressure balloon physics leads to useful insights regarding design constraints. Assume for simplicity that we can make a perfect balloon without distortions and that the load lines, seals and fixtures have negligible weight. The weight of such a balloon structure is the surface area of the sphere times the thickness of the film times the weight of the film per unit volume. The lifting capacity of the balloon is its volume times density of the displaced air minus the weight of the structure including lifting gas. Consider each of the elements of this simple design separately.

The first is the buoyancy which is the net mass of the displaced air. Air, molecular weight (MW) 32, is replaced by lighter helium, MW 4, or hydrogen, MW 2. Each molecule regardless of weight occupies the same volume.

$$Vol = \frac{4}{3} \pi r^3$$

and

$$\rho = P \frac{MW}{R_0 T_{abs}}$$

Where r is the balloon radius, ρ is the density, T is absolute temperature of the displaced air and R_0 is the universal gas constant. The net buoyancy, B , is the difference between the mass of the displaced air and mass of the internal gas.

$$B = g Vol (\rho_{air} - \rho_{gas}) \\ = g Vol \left(\frac{P_{air} MW_{air}}{R_0 T_{air}} - \frac{P_{gas} MW_{gas}}{R_0 T_{gas}} \right)$$

In order to simplify the above equation, we need to consider the initial conditions of the system during launch. We will fill the balloon with the exact amount of gas needed to keep it full during all anticipated flight conditions. Ideally, at the minimum internal gas temperature, the internal balloon pressure exactly equals the outside air pressure. Since the quantity of gas does not change during the flight, there is a point at float altitude and natural buoyancy where $P_{air} = P_{gas}$ and $T_{air} = T_{gas}$. Choosing the exact quantity of gas required to meet

these conditions is critical for a successful launch. In an actual balloon, we design for a slight safety margin overpressure so that when the gas temperature is at the minimum expected value for the flight the balloon remains inflated. For our purposes, the error is negligible and we can simplify the net buoyancy equation.

$$B - g P_{air} \left(\frac{MW_{air} - MW_{gas}}{R_0 T_{air}} \right) Vol$$

The structural weight is the weight of the film envelope. To determine the film weight the thickness must be calculated. The balloon film must carry the superpressures within the balloon. These pressures can be quite high when the sun heats the lifting gas. The thickness can be expressed as a function of the pressure difference, ΔP , across the envelop and the radius, r , of the balloon, assuming that we can specify a custom film thickness. Thickness is given by thin shell theory as:

$$t = \Delta P \frac{r}{2\sigma}$$

where σ is the design strength of the film material. The surface area of a sphere is

$$A = 4\pi r^2$$

The mass of the balloon material is the surface area times the thickness times the material density

$$\begin{aligned} \text{Balloon Mass} &= \rho_{mat} \frac{\Delta P r}{2\sigma} 4\pi r^2 \\ &= \frac{\rho}{\sigma} (2\pi r^3) \Delta P \\ &= \Delta P \left(1.5 \frac{\rho}{\sigma} \right) Vol \end{aligned}$$

From the above equation we see that the balloon structural weight depends on volume, the superpressure and the weight-to-strength ratio of the material. The superpressure must be calculated from the expected supertemperature. The choice of maximum and minimum operating temperature is very critical to the design process. Detailed analysis of heat transfer and film's thermal properties must be done. For now, we will assume that the temperature limits have been determined. In order to relate superpressure to temperature, we employ the ideal gas law and the assumption that for the

coldest design internal gas temperature (T_{\min}), we have filled the balloon at launch with exactly enough gas to keep it fully inflated. Therefore, at T_{\min} , $P_{\text{in}} = P_{\text{air}}$. We also assume a maximum supertemperature, T_{\max} , from thermodynamic analysis. These quantities can be related to express ΔP in terms of the chosen supertemperature ratio because the volume of the system is assumed to be constant in this example. The ideal gas law states

$$\frac{P_{\min}}{T_{\min}} = \frac{P_{\max}}{T_{\max}}$$

and

$$\Delta P = P_{\max} - P_{\min}$$

combining

$$\Delta P = P_{\text{air}} \left(\frac{T_{\max}}{T_{\min}} - 1 \right)$$

The total structural weight of the balloon becomes:

$$\text{Weight} = g P_{\text{air}} \left(1.5 \frac{\rho}{\sigma} \left(\frac{T_{\max}}{T_{\min}} - 1 \right) \right) \text{Vol}(r)$$

The final step is to combine the buoyancy minus structural weight.

$$\text{Gross Lift} = g P_{\text{air}} \left(\frac{MW_{\text{air}} - MW_{\text{gas}}}{R_0 T_{\text{air}}} - 1.5 \frac{\rho}{\sigma} \left(\frac{T_{\max}}{T_{\min}} - 1 \right) \right) \text{Vol}(r) \quad (\text{A.1})$$

Equation A.1 represents some simplifying assumptions. First, the effects of structural elements such as load lines and seaming tapes are ignored. Load lines are a function of the balloon circumference r and seams are a function of the surface area r^2 . These terms will be more significant in a smaller balloon than in a larger one.

Air pressure varies exponentially with altitude. In general,

$$P_{air}(h) = P_0 e^{\left(-\frac{h}{Scale\ Height}\right)} \quad (A.2)$$

$$= P_0 2^{\left(-\frac{h}{18,000}\right)}$$

Equation A.2 is simply the exponential variation of pressure with altitude. For clarity, base 2 is shown and can be interpreted as decreasing ambient air pressure by one half for every 18,000 feet of increased float altitude. 18000 feet is called the scale height, and its value depends on the units of measure and the exponential base. Its value is very close to constant for the whole atmosphere.

APPENDIX C

Solar Cells

The obvious choice for a long duration balloon prime power is solar energy. Not only is the environment cloud free but the solar intensity is not filtered by the atmosphere. Photovoltaic, PV technology powers most satellites and the technology has made major gains over the past few years. Today, there are several approaches, (crystalline silicone, gallium arsenide, amorphous silicone, copper indium diselenide and cadmium telluride), which have grown out of semiconductor research that show promise in dramatically improving solar capability. Growth will likely continue over the next decade to a point where systems become inexpensive, lightweight and efficient. For a balloon system the cost, weight per watt, UV resistance and durability are all important parameters.

The sun emits a broad spectrum of energy but solar cells have a limited absorption band depending on the type of cell technology used. At altitude, the total incident solar energy is around 1.2 KWatt/M² and an extra hour is available because of the earlier sunrise and later sunset. The basic solar cell is a semiconductor whose atoms absorb light, freeing electrons and creating current carrying holes. Individual cells are arranged into large arrays to form power generation systems. The efficiency of the conversion is a fundamental parameter of the technology selected. The selective absorption is one of the primary reason for loss of efficiency. Early devices achieved efficiencies of around 6% but today laboratory systems boast efficiencies as high as 36% under ideal conditions. A good operational solar system today operates at around 15% efficiency.

As an example of the rapid changes in basic technology, the Kopin Corporation and Boeing Aerospace announced in April of 1990 the fabrication of a new technology solar array. The array uses a thin-film, tandem cell approach developed for satellites that claims a 22.6% efficiency in a simulated space environment. The tandem cell is a combination of a single-crystal gallium arsenide (GaAs), a copper indium diselenide (CuInSe₂) and a layer of cadmium zinc sulphur (CdZnS). The top cell collects light in the 400-900 nm range while the other collects in the 900-1200 nm portion of the spectrum. The theoretical conversion limit of the tandem approach is 35-40%. This development has the potential to produce an array with a specific power approaching 750 W/kg as compared to a silicon array of about 100 W/kg. Solvonic Corporation claims that their newest light weight amorphous silicon arrays may be capable of as much as 800W/kg. The costs for these exotic arrays is not practical for operational systems today, but the future for solar technology is promising. Table 1 contains a listing of technologies, costs and weights.

Actively pointing the array at the sun is generally not usually practical in a balloon

system. Instead, a pyramid with arrays on each of the three faces and sometimes the bottom is suspended below the payload. Solar insolation is proportional to the cosine of the angle between the sun line and the normal of the array. The optimum inclination of the solar panels is a function of the balloon's latitude and time of year and can be optimized based on expected operational conditions. Albedo from clouds below the balloon can add significant additional reflected energy but its value is difficult to predict and arrays on the bottom of the collector is used only in special cases.

SOLAR CELL TECHNOLOGY

TECHNOLOGY:	Watts/lb	Watts/ft ²	Cell Efficiency	\$/Watts	Qualities
Crystal Silicone	80	18	16%	125	8 mil backing
A-Si (Solvionics)	100	5	10%	120	Current Product
GaAs (1995)	300	35	28%	500	2 mil, ultra lite
A-Si (Solvionics 1992)	360	13	13%	120	Projections

Table C-1 Comparison of various cell technologies for use in LDFFF flights.

REFERENCES

1. Science Applications International Corporation, "Small Payloads ELV System Study," Report No. SAIC-89/1638, Study No. SAIC 1-120-684-S27, November 1989, for NASA Lewis Research Center, Cleveland, Ohio.
2. Study Committee, Long Duration Balloon Flight, R. Stephen White, Chairman, "A Plan for Long Duration Scientific Ballooning," Report, January 1983.
Dr. Lew Allen, "Remote Sensing of Global Change," Signal, September 1989, pp. 23-28.
3. Murry L. Salby and Rolando R. Garcia, "Dynamical Perturbations to the Ozone Layer," Physics Today, March 1990.
4. Alvin L. Morris, Editor, Scientific Ballooning Handbook, NCAR Technical Note NCAR-TN/IA-99, May 1975, National Center for Atmospheric Research, Boulder, CO.
5. T. F. Heinsheimer, B. C. Corn, "Evaluation of Design Alternatives for the Exploration of Mars by Balloon," Final Report of Titan Systems, Inc. for NASA Headquarters, Office of Exploration Code Z, Washington, DC, Contract Number NASW-4457, 2 February 1990.
6. Justin H. Smalley and Neil E. Carlson, "A Long-Duration Balloon System for Middle Atmosphere Measurements," Presented at COSPAR Symposium 10, Advances in Balloon Technology, Toulouse, France, 7-8 July 1986, COSPAR ID 10.2.1, National Center for Atmospheric Research, Boulder, CO 80302.
7. Vincent E. Lally, "Superpressure Balloons for Horizontal Soundings of the Atmosphere," June 1967, NCAR-TN-28, October 1971 Reissue, National Center for Atmospheric Research, Boulder, Colorado.
8. C. Chocoi, W. Massey, R. Hoard, J. Hendricks, and M. Newman, "Kestrel 3 Program Final Report," April 17, 1989, Lawrence Livermore National Laboratory, Livermore, CA,

9. Ronald M. Nagatani, Alvin J. Miller, Keith W. Johnson, Melvyn E. Gelman, "An Eight-Year Climatology of Meteorological and SBUV Ozone Data," NOAA Technical Report NWS 40, National Meteorological Center, Camp Springs, MD, March 1988.
10. Robert L. Hawkins, "Expendable Air Vehicles/High Altitude Balloon Technology (Balloon Drift Pattern Simulation)," Final Technical Report, CHR/89-1909,28 February 1989, Coleman Research Corporation, Huntsville, AL.
11. C. G. Justus, G. R. Fletcher, F. E. Gramling, and W. B. Pace, "The NASA/MSFC Global Reference Atmosphere Model - MOD 3 (with Spherical Harmonic Wind Model)," NASA CR-3256, 1980.
12. David G. Andrews, James R. Hoton, Conway B. Leovy, Middle Atmosphere Dynamics, Vol. 40 in the International Geophysics Series, Academic Press, Inc., 1987.